Jose Costa

<jacosta@ua.pt>

SIMULATION OF THE DYNAMIC BEHAVIOR OF THE GAS RELEASED DURING THE PYROLYSIS PROCESS, WHEN IT PASSES THROUGH A GAS CYCLONE

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Final report presented to the University of Aveiro in partial fulfillment of the requirements for the degree of Master of Science in Mechanical Engineering, developed under scientific orientation of Professor Ing. Pavel Kolat, DrSc, Professor Doc. RNDr. Kozubková Milada, CSc and Eng. Rui Teixeira in the Department of Energy and Department of Hydrodynamics and Hydraulic Equipment in VŠB - Technical University of Ostrava, respectively.

This is dedicated to my beloved parents Joaquim Francisco Araújo Costa and Carolina da Silva Oliveira Costa.

the jury

examinares committee

Professor Ing. Pavel Kolat, DrSc.
Professor of the Department of Energy in VŠB - Technical University of Ostrava

Eng. Rui Teixeira
PhD Student and Assistant in the Department of Energy in VŠB - Technical University of Ostrava

Ing. Mario Balcó
Engineer in ArrowLine a.s. company

people envolved

supervisor	Professor Ing. Pavel Kolat, DrSc. Professor of the Department of Energy in VŠB - Technical University of Ostrava
co-supervisor	Eng. Rui Teixeira PhD Student and Assistant in the Department of Energy in VŠB - Technical University of Ostrava
collaborators	Professor Doc. RNDr. Kozubková Milada, CSc. Professor of the Department of Hydrodynamics and Hydraulic Equipment in VŠB - Technical University of Ostrava
	Ing. Mario Balcó Engineer in ArrowLine a.s. company
	Ing. Tomáš Blejchař Ph.D. Engineer in Orgrez, a.s. company

"All truths are easy to understand once they are discovered; the point is to discover them."

Galileo Galilei

acknowledgments

"Approach each new problem not with a view of finding what you hope will be there, but to get the truth, the realities that must be grappled with. You may not like what you find. In that case you are entitled to try to change it."

Bernard M. Baruch

In the spirit of this dictum, I would like to express my thanks to all who have joyfully contributed to this thesis with their own "changes" – be it ideas, technical expertise or feedback, as well as by bearing over with me during this intense time.

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keywords Cyclone, Dynamic Simulation, Pyrolyse, Gas, Species, Particles.

abstract

A computational fluid dynamic (CFD) model was applied for a cyclone used in a conversion unit in Ostrava (Czech Republic). The purpose of this work was to investigate the labor conditions of the cyclone and provide the information how to optimize it for a good behavior of the gas which is released during the pyrolysis process.

In accordance with the main objective, the modelling provided the knowledge of the temperature distribution over the gas inside the cyclone, the range of velocity values, the path lines of the gas and the trajectory of the heavy particles, for different operational conditions. The CFD computer code FLUENT was used for the three dimensional simulation and Gambit as pre-processor to generate the model and create the mesh. Operational data was used to model the cyclone and the gas in the simulations. The RNG k-ε turbulence model together with wall functions and species characterization was adapted for characterization of the gas behaviour and also the simulation was executed in double precision (ddp) mode.

The simulations have pointed out that a good range of values to the boundary conditions principally a good value of mass flow can influence in a positive or negative way the behavior of the gas inside the cyclone. In this work was observed that for the conditions which the cyclone is working the efficiency is not good, the mass flow is too small therefore the cyclone should be small.

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ACRONYMS

CFD	Computational Fluid Dynamics
DCU	Delayed Coking Unit
GPL	Liquefied Petroleum Gas
FCC	Fluid Catalytic Cracking
TSS	Third Stage Systems
ER	Equivalence Ratio
PS	Polystyrene
PE	Polyethylene
PP	Polypropylene
PET	Polyethylene Terephthalate
RNG	Renormalization-Group

NOMENCLATURE

Ø	diameter (mm)
g	gravity (m/s^2)
T	temperature (K)
T_0	atmospheric temperature (K)
T_{inlet}	inlet temperature (K)
R	universal gas constant (Nm/kmol K)
r	specific gas constant ($J\ kg^{-1}\ K^{-1}$)
P_0	atmospheric pressure (Pa)
M	atomic weight (Kg/kgmol)
ρ	density (kg/m^3)
ρ_{mix}	density of the mixture (kg/m^3)
Q	volume flow rate (m^3/h)
$\dot{m}$	mass flow rate (kg/s)
Yi	mass fraction
V_f	volume fraction
CH_4	methane
H_2	hydrogen
C_2H_4	ethylene
C_2H_6	ethane
C_3H_6	propylene
CO_2	carbon-dioxide

1 AIM OF THE WORK

This dissertation is about a project which is being developed by the Arrow Line a. s. in cooperation with the Technical University of Ostrava and focus in a moving bed pyrolysis unit to convert solid wastes into usable energy by the society.

The gas released by the process will be filtered by a cyclone located in the hot zone of the installation; all the work will be concentrated in this specific point. The gas movement will be forced by a fan located in the end of the pipeline that imposes the flow to the outlet of the cyclone which now is working without fan.

There are some expected values of the pressure on the entrance of the cyclone; however they must be supported by some calculations considering the rate by which the fuel is converting in gas.

The main goal of the project is to find the best set of values that insures the good behaviour of the gas inside the cyclone releasing the dust and the heavy particles flowing in it into a deposit under the cyclone. These results will be found using software which simulates dynamic behaviour of the gases and will allow us to see all the important points inside the cyclone with the finality of comment them and look for improvements in order to find the best efficiencies for the system in cause.

2 INTRODUCTION

2.1. Computational Fluid Dynamics

The limitations of human mind are such that it cannot hold the behaviour of its complex surroundings and creations in one operation and then for such problems we are forced to use CFD (Computational Fluid Dynamics) programs. CFD was developed over 40 years ago by engineers and mathematicians to solve heat and mass transfer problems in aeronautics, vehicle aerodynamics, chemical engineering, nuclear design and safety, ventilation and industrial design. Whilst the fundamental equations of fluid motion that formed the basis of such codes had been well known since the 19th century, their solution for problems with complex geometry and boundary conditions required the development of efficient numerical solution techniques and the ability to implement these on digital computers. The development of this technology in the 1950s and 1960s made such research possible, and CFD was one of the first areas to take advantage of the newly emergent field of scientific computing. In the process, it was soon realized that CFD could be an alternative to physical modelling in many areas of fluid dynamics, with its advantages of lower cost and greater flexibility.

Modern CFD techniques emerged between the late 1960s and early 1970s when fluid flow investigations were largely experiment based and only very simple fluid flow problems could be accurately numerically solved. With the rapid development of modern computational techniques and numerical solution methodologies over the last few decades, CFD has now been widely used in various industrial applications for investigating a vast range of industrial and environmental problems [1].

In this work the used tool was FLUENT 6.3, this program is a CFD system for numerical solution of the fluid dynamics problems. Numerical solution is based on the finite volume method. Software includes tools for stationary and non-stationary analyses of fluid flow, discrete phases, multi-phase flow, heat transfer, phase changes, chemical reactions, combustion processes and moving boundaries

problems. FLUENT is capable to process all types of meshes (2D, 3D, axis symmetric, hybrid, non-conformal, transition and boundary layers).

The model geometry of the cyclone, with mesh, will be an input to FLUENT and then in the domain of the program parameters like material properties, thermo-dynamical relations and conditions of solution can be changed or created as well as define the operating and boundary conditions.

2.2. Overview about Cyclones

Cyclonic is a method of removing particulates from an air, gas or water stream, without the use of filters, through vortex separation. Rotational effects and gravity are used to separate mixtures of solids and fluids.

A high speed rotating flow is established within a cylindrical or conical container called a cyclone. Air flows in a spiral pattern, beginning at the top (wide end) of the cyclone and ending at the bottom (narrow) end before exiting the cyclone in a straight stream through the center of the cyclone and out the top. Larger (denser) particles in the rotating stream have too much inertia to follow the tight curve of the stream and strike the outside wall, falling then to the bottom of the cyclone where they can be removed. In a conical system, as the rotating flow moves towards the narrow end of the cyclone the rotational radius of the stream is reduced, separating smaller and smaller particles. The cyclone geometry, together with flow rate, defines the cut point of the cyclone. This is the size of particle that will be removed from the stream with 50% efficiency. Particles larger than the cut point will be removed with a greater efficiency and smaller particles with a lower efficiency [2].

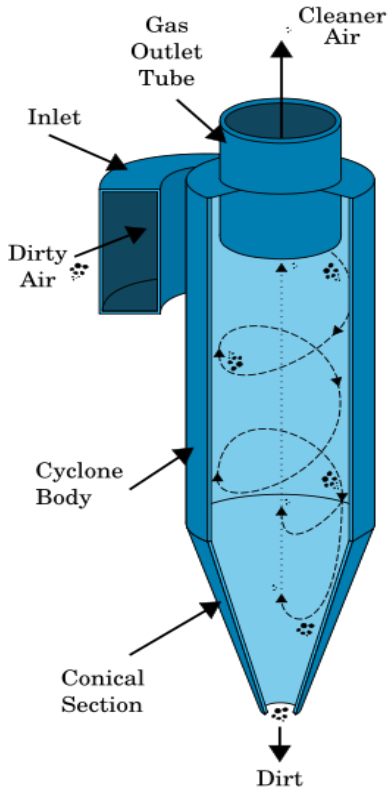

Figure 1: Cyclone standard configuration [2]

2.2.1. Cyclone Separator

Cyclone separators are normally used for the collection of coarse dust particles. The dusty air is introduced in the cyclone separator from the top through the inlet pipe which is tangential to the cylindrical portion of the cyclone. Thus the gases move downwards in whirling motion forming a peripheral vertex and giving rise to centrifugal forces, resulting in throwing of dust particles towards the wall of the cyclone and moving downwards into the hopper. The gas after reaching the end of the conical portion changes it direction and moves upwards towards the outlet forming an inner vertex. Due to this upward movement of gases against gravity more dust particles are separated and fall into the conical hopper for subsequent removal.

Figure 2: Cyclone separator [3]

These equipments are used for control of coarse dust of high concentration. The dust laden gases enter the separator under pressure or suction. The dust particles are separated due to the whirling action and ventex formation and are collected in the hopper. To accommodate more volume of gases and higher efficiency of dust separation, multi clones are also provided [4]. Same advantages in the use of cyclones are:

- Adequate to coarse dust content gas
- Adequate to high dust concentration
- Trouble free long life
- High collection efficiency (Coarse Dust)
- Low initial cost

In resume we can say that cyclones are the principal type of gas-solid separators because of their simple construction, capacity to operate at high pressures and temperatures.

2.2.2. Cyclones in the Industry

Cyclones are simple mechanical devices for removing relatively large particles (> 5 to 10 μm) from gas streams. Actually, they are more commonly applied than we may realize.

They are used by:

- **Environmental Engineers** to remove particulate pollutants.
- **Chemical Engineers** and **Mechanical Engineers** to collect valuable particle products.
- **Industrial Hygienists** to sample particles in working environments.
- **Pharmaceutists** to classify their powdered drugs.
- **Woodworking industry**.

One of the most popular examples of industries that use this kind of equipment is the woodworking industry, is easily to see this cyclones just by an outside view from the factories.

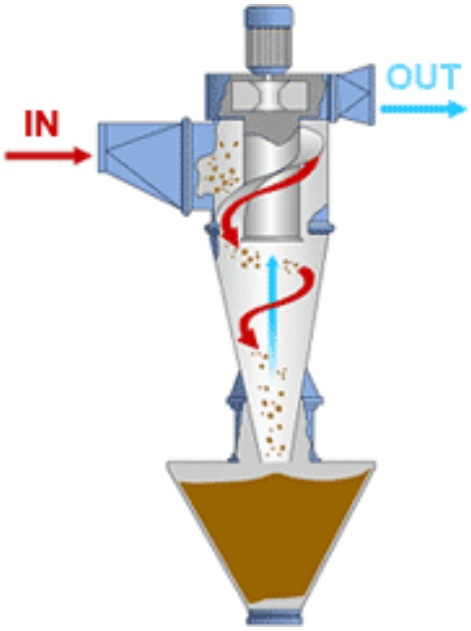

Figure 3: Cyclone dust collector [5]

Woodworking equipment is always a prime candidate for cyclone use, as it is best suited to handle those larger pieces of wood dust. In most cases, a cyclone dust collector is used as a pre-filter, depending on the circumstance.

Some specialists refer to these machines as "high efficiency golf ball collectors", since they are rated to handle mainly particles that are larger than 10 microns in diameter (in the air quality industry, these would be golf balls). Most applications require after-filtration or post-filtration downstream from the cyclone.

This is common in instances where finer dust particles must be captured, whether it's because of the need to re-circulate the exhaust air indoors, or if there is occupied space where the cyclone will exhaust. Basically, without after-filtration, we see "wooden snow" blasting out of the collector's outlet [5].

When that happens the neighbours properties in the way of that exhaust path will not be so happy with that.

- **Cement industries**

Figure 4: Cyclone dust collector in cement industry [6]

In this type of industry the dust control equipment is joined with the manufacturing process, being extremely important in this industry.

Without suitable dust control equipment, large dust emissions will occur at several stages in the conversion of limestone (sedimentary rock) and clay (material composed primarily of fine-grained minerals), that means 20-30% of the production would be lost, and one can imagine what that would mean to the production costs.

Large cyclones are efficient in removing dust larger than 10-30 µm but higher dust collection efficiency may be obtained by using a multi-cyclone, which is a parallel arrangement of several small cyclones (0.15-0.30 mØ).The centrifugal force is greater in multi-cyclones than in large cyclones, because the radius is smaller, and the efficiency is therefore higher; most of the particles larger than 3-5 µm are collected [7]. Also in cement industries when the cyclones are not able to give sufficiently high dust removal efficiency more types of filters will continue the work, such as: scrubbers, fabric filters and electrostatic precipitators.

- **Flour mills**

In the flour mills, the cyclones are used also with the same finality as the normal industries, here the most important physical property of starch granules is their size, fines (less than 44 μm) from coarse (higher than 44 μm), because it is what distinguishes a product of high quality of one with low.

But in these industries a couple of cyclones work together, different types of cyclones but with the same goal, the main product. As it shown in the following figure they have a normal cyclone at the end of the unit line but at the first, the unit has different type of cyclones where is applied a different method of operation, they operate in inverse mode compared with what is normal.

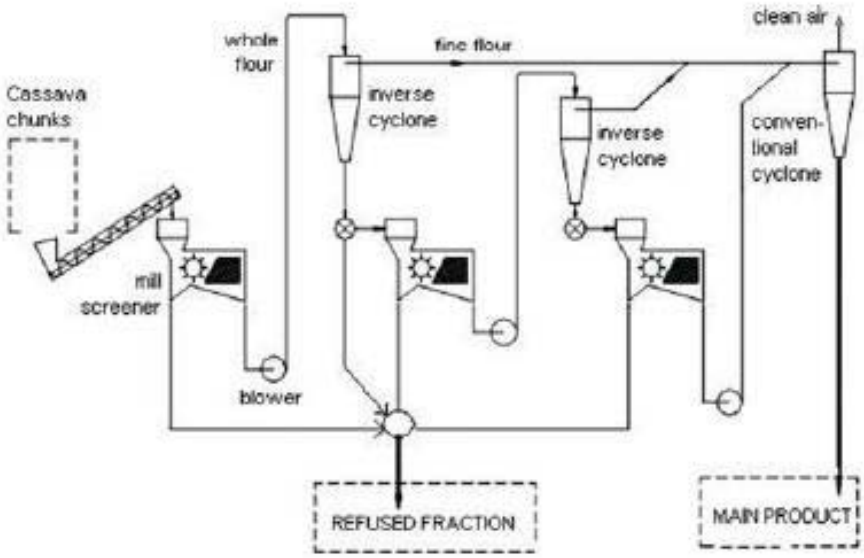

Figure 5: Plant flow layout in flour mills [8]

This layout shows the proposed process, which uses raw cassava (tropical plant) pieces (12% moisture) as a prime material, and where starch enriched flour is the main product. This technique consists of a milling process parallel to a solid-solid and solid-gas separation. The raw matter (cassava chunks) is fed toward a mill-screener device obtaining whole flour and refused fraction.

The refused fraction constitutes a by-product that is packed for other uses; in the meantime, the whole flour continues to the inverse cyclone separation (the new solid-solid separation). In this apparatus the flour is disaggregated into fine flour (< 44 mm, 87% starch) and coarse flour (> 44 mm). The course flow can be packed either as a by-product or returned to a second or third milling and separation phases. The fine flour is recovered through a conventional cyclone and constitutes the main product, as already mentioned [8].

The biggest difference between these two types of cyclones is the inlet and the outlet of the cyclone as shown in the next figure, the inlet in the conventional cyclone is situated in the tangential and the outlet above the cyclone, on the other hand the inverse cyclone has the inlet and the outlet located in the inverse position.

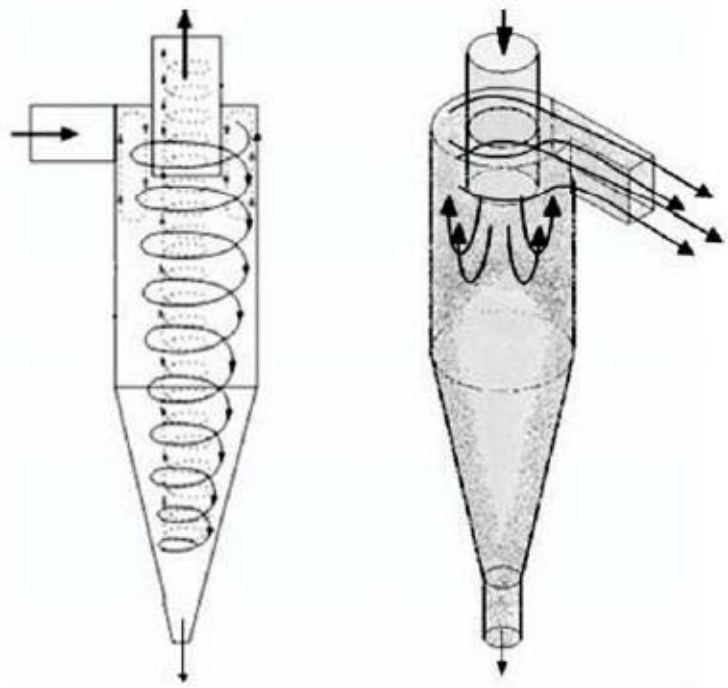

Figure 6: Conventional and Inverse Cyclone Flow Patterns [8]

Extra to the inverse cyclone, the solid-solid separation can be done by other means like: screens, conventional cyclones, commercial available third generation separators or any other applicable method but the third generation separators are unaffordable for small and medium rural producers, and conventional cyclones for this application result in extremely large devices (7 m diameter, 30 m height) which are impractical and high-priced.

- **Oil refineries**

The first process of refining oil is the primary distillation through which oil is extracted from the main fractions that give rise for petrol and diesel, all of naphtha, the solvent and kerosene (for lighting and aviation), and the GPL (cooking gas), for that cyclones are used. They remove coke (waste oil) fines from water in the delayed coking unit (DCU). The process of cooling and cutting coke from coke drums produces coke fines that are carried by the cooling / cutting water to a sluiceway or coke pit.

The water may or may not pass through a settling maze before being returned to a water storage tank for re-use. Due to the techniques used to move the coke product away from the coke drums and inefficiencies in the settling maze, coke fines tend to accumulate in the water storage tank. When these fines are recalculated with the water they cause unnecessary wear on valves, piping, heat exchangers, high pressure jet pumps, and coke cutting nozzles. Installation of cyclones to remove coke fines greatly reduces the maintenance requirements on the downstream equipment.

In oil refineries different types of cyclones are used as previously focused also on other industries.

The following figures show same examples of those cyclones:

Reactor Cyclones

Figure 7: Reactor cyclone [9]

- Reactor cyclones are cyclone separators used to separate hydrocarbon vapors and stripping steam from Fluid Catalytic Cracking (FCC) catalyst.
- Reactor cyclones are constructed from refractory lined carbon steel or low alloy steel or even stainless steel and come in many different configurations.
- Reactor cyclones can be attached directly to the riser with a second stage following in a closed coupled system or can be open coupled. They can also be a single stage cyclone preceded by a riser termination device [9].

Regenerator Cyclones

Figure 8: Regenerator cyclone [9]

- These cyclones are used to separate catalyst from flue gas created when the carbon or coke is burned with air from the FCC catalyst.
- And are designed to withstand very abrasive service at a temperature of 1450 degrees F (787,8 °C) [9].

Third Stage Separators

Figure 9: Third Stage Separator [9]

- Unlike traditional third stage units designed to eliminate particles >10micron diameter and high inlet and outlet velocities, characterized by a large number of small cyclone, third stage systems (TSS) are designed to collect as much catalyst as possible while limiting system erosion and catalyst attrition.
- TSS utilize a pressure vessel to contain fewer, larger diameter, high efficiency cyclones sized to maintain inlet velocity (with refractory lined cyclones, erosion on cyclone surface is reduced to an acceptable level).
- From the final collection hopper, the fines can be off-loaded to a truck or disposal container [9].

Fourth Stage System and Critical Orifice

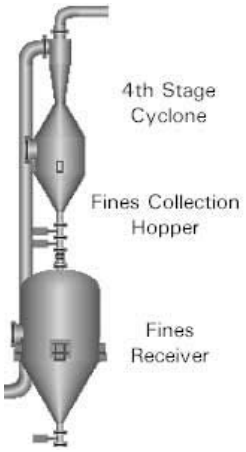

Figure 10: Fourth Stage Cyclone [9]

The cyclone Vessel, which is the common hopper for the cyclone catalyst discharge, is designed to hold the catalyst collected over several days. However, normally the catalyst from the cyclone Vessel is continuously conveyed to the 4th stage cyclone by a small amount of gas, usually from 1 to 3% of the gases entering the cyclones. During the travel through the uninsulated line and the 4th stage cyclone, a considerable amount of heat is lost from the catalyst and gases. Additional cooling of the catalyst occurs in the fines collection Vessel. The gases from the 4th Stage Cyclone pass through a critical orifice where the gas pressure is

reduced for discharge through the stack. When the Fines Collection Vessel is to be emptied into a closed truck for transport to a land fill, the valve above the vessel is closed, a vent valve is opened to relieve the pressure, and the valve beneath the vessel is opened so that the catalyst may discharge into the truck [9].

2.3. Conversion Methods

2.3.1. Introduction

Energy has become an item of top priority on our lives. The increase in energy prices and the impact of energy consumption on the environment, the limitations of the fossil fuel and the entry in force of Kyoto protocol have all of them made the energy situation a focal point of attention.

As solution for this situation, renewable sources of energy are increasingly used nowadays. There are several methods to convert different kind of energies overspread by the nature in usable energy, is an important step to reach the best results from this conversion and then contribute to the decreasing of environmental impacts and maximize the efficiency of this process. The normal methods (thermo-chemical) used to convert biomass or any other kind of wastes in usable energy are the solution for many of these wastes, normally useless and in some cases a big problem because of the environmental impact that they made. Those methods are combustion, gasification and pyrolysis.

The combustion process is a chemical process in which a substance reacts rapidly with oxygen and gives off heat, combustion has the big disadvantage that burns directly wastes without any filtration of the fuel during the burn and when this occurs high emissions of noxious gases are released generally.

Products from pyrolysis and gasification are oxidized during the combustion process. For fully oxidation presence of the sufficient amount of oxygen is necessary min Equivalence Ratio (ER) = 1. Oxygen must be well mixed with the gases formed during the combustion process and then, with the rising of the temperature kinetics reactions rise exponentially. Combustion products after fully oxidation are ash, CO_2 and H_2O. The heat produced during the process can be used directly or converted into mechanical or electrical energy but comparing combustion with gasification and pyrolysis these lasts two are more environmental friendly. The biggest advantage is that these methods convert the biomass and the wastes in a fuel which can be treated and then burned in some high efficiency gas turbine or in the case of the liquids the fuel can reach a high quality to be used as a fuel for diesel or benzene

engines after some treatments thereby reducing emissions and improving the energy production from the same quantity of waste.

Gasification is a high-temperature process that is optimized to produce a fuel gas with a minimum of liquids and solids, is a complete thermal breakdown of the biomass/waste particles in the presence of any oxidant agent when the equivalent ratio is lower than 1 (ER<1). Gasification, which is more proven than pyrolysis, consists of heating the feed material in a vessel and water may or may not be added. Decomposition reactions take place, and a mixture of hydrogen and CO are the predominant gas products, along with water, methane, and CO2.

Pyrolysis is a process for converting solid feedstocks into a mixture of solid, liquid, and gaseous products. It is a process involving high temperature process (550-900°C), that depends in which conditions the reactor is working and also which kind of temperature values the material of the reactor can operate. What distinguishes this process in relation to the gasification is the absence of any oxidant agent and that means an equivalence ratio equal to 0, ER=0.

Factors such as heating rate, temperature, pressure and reaction time has strongly influence in the amount and composition of the formed products, to maximize the production of liquid fuels and chemical feedstock's directly from a feedstock requires careful reaction control and fast heating and cooling rates to prevent the liquids that do form from breaking down to gases.

2.3.2. Gasification Technologies - Reactors

Various gasification technologies are employed for the gasification of solid fuels but there are principally three that are the base of all the reactors that have been developed by until now:

- Fixed-bed gasifiers
- Fluidized-bed gasifiers
- Entrained flow gasifiers

All these processes can be operated at ambient or increased pressure and serve the purpose of thermochemical conversion of solid biomass/waste into a secondary fuel in a fluid state. For thermochemical conversion it is necessary to supply sufficiently solid biomass and gasification media, the resident time is also important as well as provide a pressure and temperature regime by means of suitable gas control and geometrical construction of the reactor.

An important characteristic value that is valid for all gasification processes for any fuel is the degree of cold gas efficiency. This is defined as the ratio of fuel energy used to the chemical energy bound in the cooled and cleaned stream of producer gas.

1.1.1.1. Fixed-bed reactors

In fixed bed reactors a fuel bulk filling is always in the reactor chamber. From the top of the reactor comes the biomass and then is entering the reactor trough an opening or sluice on the top of the reactor head. After that the gravity does the work and the biomass flows downward until that fuel bulk filling.

Inside fixed bed systems exists two types of models, the up and down-draft gasifier, this because of the relative direction of gas stream and the fuel bed movement.

Fixed-bed updraft gasifier

In this model, the produced gas is collected in the top of the gasifier. The gasification media (air, oxygen, steam) enters the reactor in the area of the grate. With this method of gasification clearly defined reaction zones arise in the bulk filling. The heat of the produced raw gas is used to dry the fuel and help to start the pyrolysis.

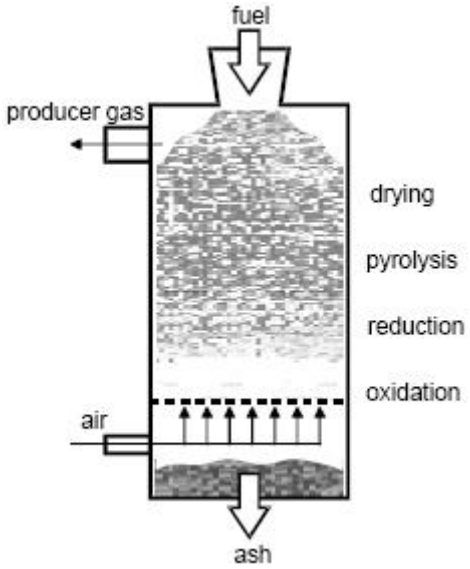

Figure 11: Schematic diagram of an updraft gasifier [10]

As shown in the schematic diagram in figure 11, the processes that occur during the different stages of the fuel are at the first drying followed by pyrolysis, reduction and oxidation. The gasification media can be air, steam or oxygen.

Products of decomposition released in the pyrolysis zone and the steam released as a result of fuel drying are discharged directly out of the reactor with the producer gas. The problematical pyrolysis gases are not conducted through any hot zone and can therefore not be suitably split up or oxidized. The tar content in the raw gas can thus reach values over 100 g/m_n^3 during gasification of the biomass, is to much higher compare with tar content in the case of gasification in the downdraft which is about 1 g/m_n^3.

In the next table are shown the fundamental requirements for the gasification of biomass.

Table 1: Requirements for fuel quality with updraft gasification [10]

Water content	< 40 % $_{Mass, wet}$
Grain size	0.5 – 20 cm
Share of fine particles	< 30 %$_{Mass, wet}$ ($\leq$ 5mm)
Ash content	< 6 % $_{Mass, dry}$

The steam accumulated in the drying zone drawn off directly with the stream of the producer gas like the pyrolysis vapors.

The updraft gasification take care better fuels with high water content. The ash melting point is usually not exceeded and slagging problems can therefore be prevented.

Fixed-bed downdraft gasifier

The second model for fixed bed gasification is the downdraft gasifier. In this type of gasifier the producer gas is collected under of the gasifier as we can see in figure 12. The drying/pyrolysis zone lies above the oxidation zone and is supplied with the necessary process heat primarily through thermal conduction in the bulk filling. In the oxidation zone primarily vaporous pyrolysis products react with the input gasification medium and the gases (CO2 und H2O) leaking from the oxidation zone are reduced to CO und H2 by the glowing charcoal of the lower lying reduction zone.

As shown in the following figure the gases originating in the pyrolysis zone will have to pass through the oxidation zone, which is called as “hot treatment zone for tar compounds” and that is a benefit/advantage to the gas because it will put the gas stable. The organic compounds that are still contained in the producer gas after conversion of the pyrolysis vapors in the hot oxidation zone at 1000°C to 1200 °C are classified in as tertiary tar compounds. These processes can be operated with cold gas efficiencies between 60% and 80%.

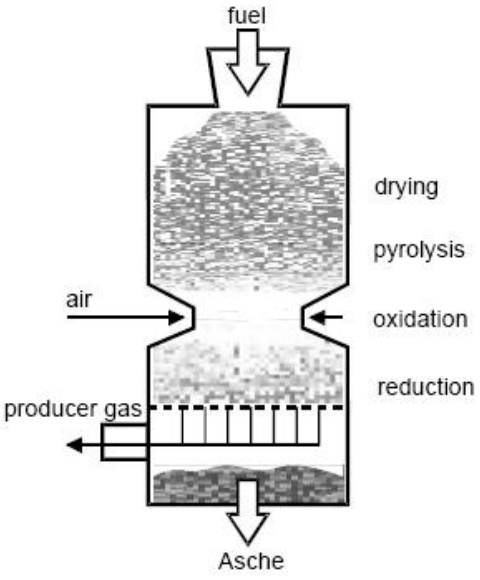

Figure 12: Schematic diagram of a downdraft gasifier [10]

In this type of gasifier the fed can be made via radial and when that's happens a problem can occur, the problem is to ensure depth penetration of the medium into the fuel bed and avouch the oxidation zone is uniform along the cross section.

A solution or improvement is an additional feeding of the medium through a central pipe can help to bring about a uniform distribution of the hot areas over the entire reactor cross-section. These problems of ensuring uniform reaction conditions of the gasification medium are responsible for the limit in up scaling downdraft gasifiers.

The fuel thermal output of 1 MW_{th} is recommended as the upper limit of sensible up scaling for an individual gasification reactor.

Table 2: Requirements for fuel quality with downdraft gasification [10]

Water content	10 – 25 % $_{Mass, wet}$
Grain size	2 – 20 cm
Share of fine particles	< 15 %$_{Mass, wet}$ ($\leq$ 5mm)
Ash content	< 6 % $_{Mass, dry}$

The scheme in figure 12 shows a simplification of the method with fuel feeding from top and where the gasification medium is fed near the throat section, furthermore are presently being constructed downdraft gasifiers whose combustion chamber is designed cylindrically over the entire height without tapering where the gasification medium and the fuel are fed together through the open upper section of the reactor.

A combination of downdraft and updraft gasification appears as third possibility, it's called double fire gasifier.

In the upper part of the gasifier the fuel is converted by means of a downdraft. From the details on downdraft gasification given above it is clear that a certain amount of un-reacted charcoal accumulates in the reduction zone. The purpose of two-zone gasification is to use updraft gasification to convert this residual fuel in the grate area completely into producer gas, one great advantage of this combination. The next scheme in figure 13 shows the principals of this method.

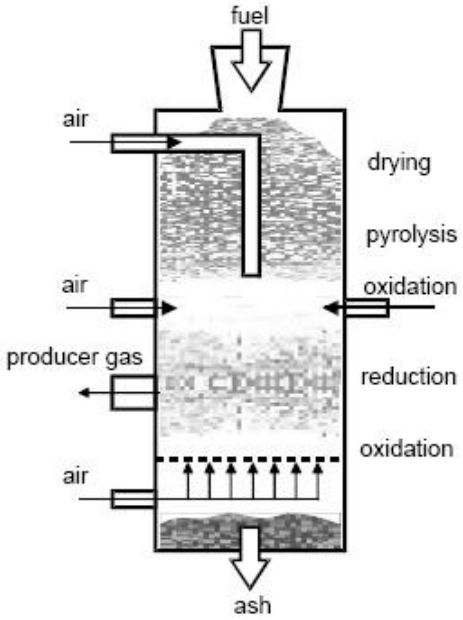

Figure 13: Double fire gasifier [10]

Another advantage of this process is the possibility of, with a suitable location of the collecting duct, the crude gas produced in descending gasification goes through a further hot zone and this may help a conversion of pyrolysis vapors that are still present. After that the products keep going to the next stage where a partial oxidation will take place in the gasifier.

More models are being developed by many universities, each one with their own characteristics, figure 14 shows an example, from Technical University of Denmark. The process is characterized by two separated reactors: The first is an indirectly heated screw feeder, in which pyrolysis is realized, the second zone is a combined reactor for partial oxidation of pyrolysis gas (main tar conversion) and for the heterogeneous gas char reaction (reduction/gasification process). The main advantage of these concepts is a producer gas contamination with tarry compounds below 25 mg/Nm³, which allows falling below the gas engine limiting values for the producer gas utilization without any secondary gas treatment and gas cleaning [10].

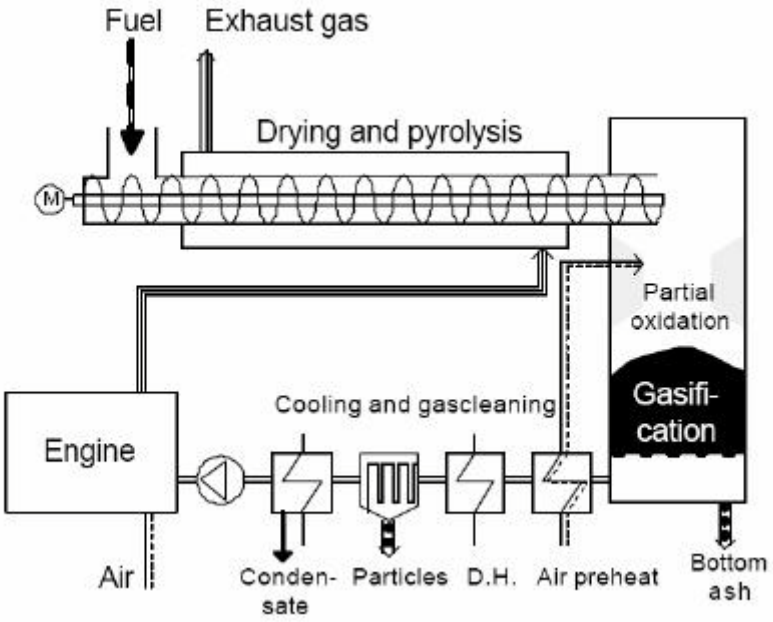

Figure 14: Two-stage gasifier of the Technical University of Denmark, DTU [10]

The following figure exemplifies the 3-stage gasifier of Thomas Koch Energi (TKE, Denmark). Comparing to the others this process has no external heat for the pyrolysis step in the staging concept. Pyrolysis is carried out by partial oxidation of the solid fuel.

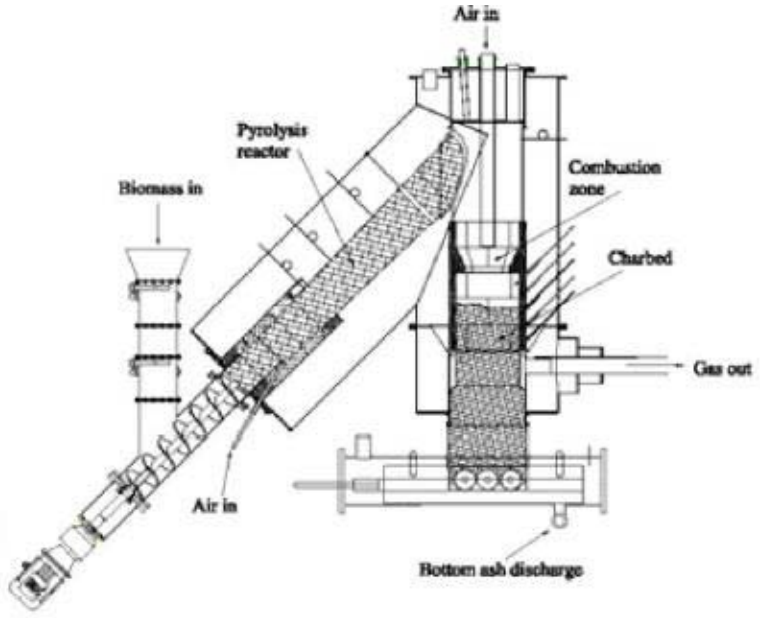

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Figure 15: TK Energy "3-staged gasifier" 400kWth [10]

The next model shows the staging principle of the CleanStgas Concept (Clean-StagedGasification) developed at Graz University of Technology in Cooperation with partners from industry. This model is characterized by different reactors where the different thermochemical reactions, pyrolysis, partial oxidation and reduction take place. The result of the three staging concepts is a low-tar producer gas below the limits of IC engines. Therefore, no tar precipitation in a wet gas cleaning and consequently no waste water treatment are needed, which brings well-known benefits for plant economics in the lower and middle range of power.

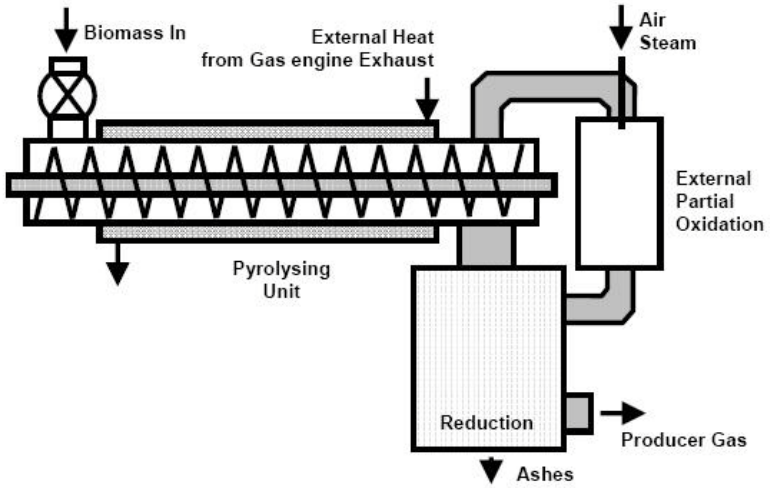


Figure 16: CleanGas Gasifier Graz University of Technology [10]

In this model the staged gasification with heat reflux from the process chain into pyrolysis results in higher cold gas efficiencies when compared with to single-stage fixed-bed gasifiers, because less air is needed for the thermal conversion of the fuel.

Another converter reactor is being developed by one company in Ostrava, Arrow Line a.s., in cooperation with Technical University of Ostrava and it's about this unit that this work is focus in. In the following figure is shown a small scheme of the reactor.

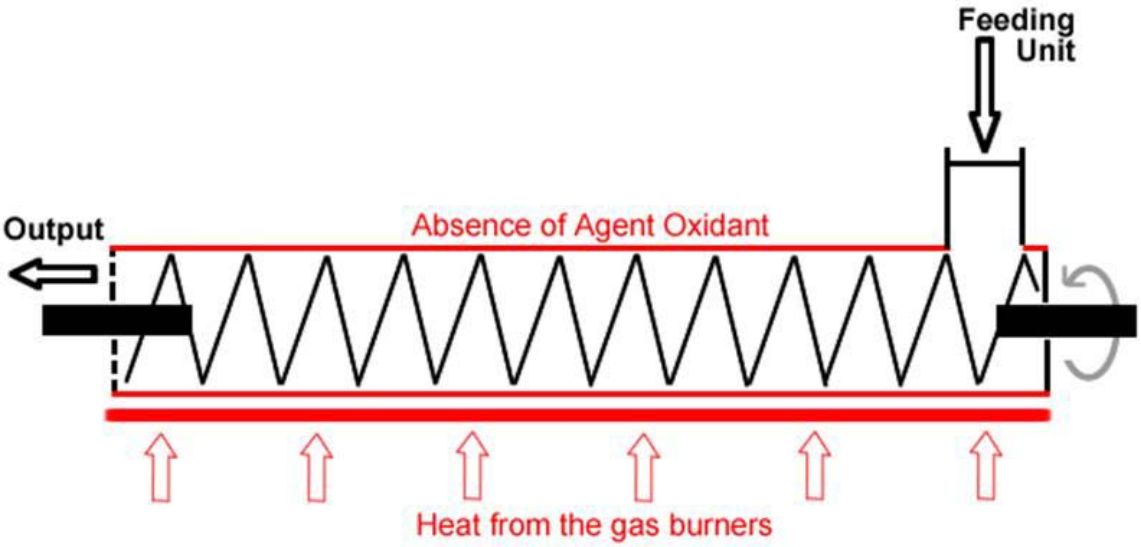


Figure 17: Pyrolysis Rector - Technical University of Ostrava

The scheme above represents the pyrolysis unit, the screw pushes the waste material though the hot zone where heat gas burners located downdraft in the reactor starts to create thermochemical reactions. The process begins with a drying of the material and then during the 4 meters of the reactor the rest of the conversion is done.

1.1.1.2. Entrained flow gasifiers

In this type of gasifiers the main difference is the grain size is generally smaller than 0.1 mm (10 µm). The fuel is carried through the reactor with the gasification medium and thereby gasified. The retention time is only a few seconds, and so gasification has to take place quickly at temperatures between 1200 and 1500°C. The high temperatures ensure a complete conversion of the hydrocarbon compounds resulting from pyrolysis of the fuel.

Pyrolysis and gasification take place at the same time. The ash melts and accumulates after adequate cooling as slag [10].

1.1.1.3. Fluidized-bed reactors

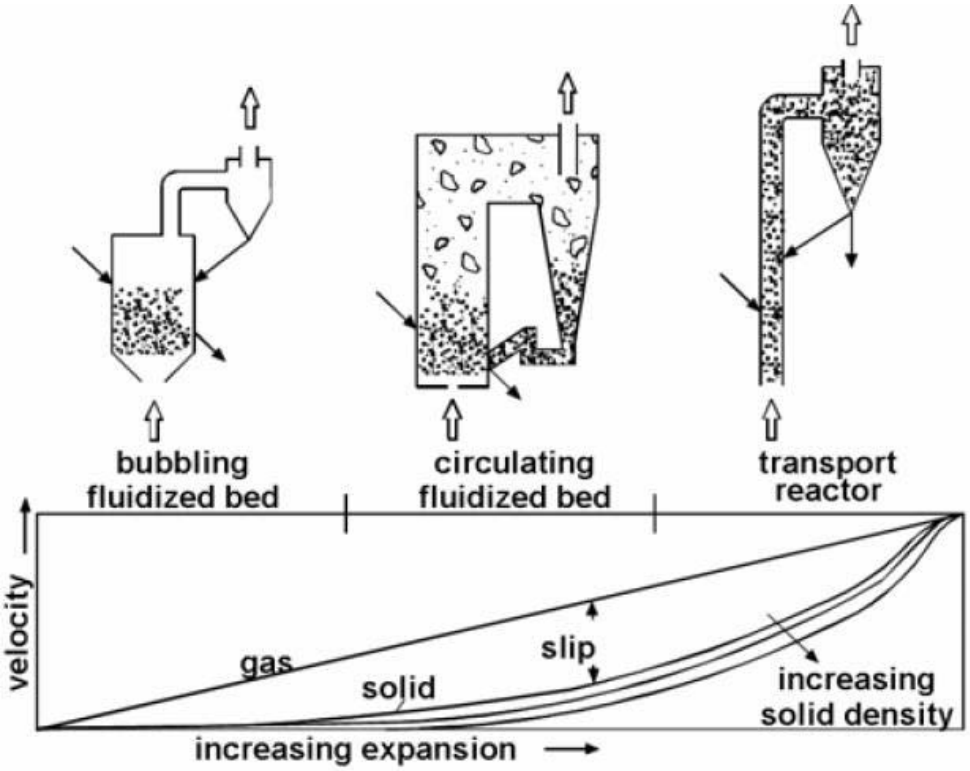


Figure 18: System for gas/solid fluidized bed reactor [10]

These types of reactors function with a fluidized mix of bed material and biomass/waste that will be gasified by the gasification medium. The gasification medium flows in though the nozzle bottom and fluidizes the bed material, this material can be inert, like quartz and or also catalytically active material. Catalytically active bed material is used for the conversion of organic contaminants in the crude gas though possible after-reactions in the gas phases. The fuel should be turned into small pieces with a maximal edge length of 50 mm to 100 mm and is fed into the fluidized or circulating fluidized bed.

The fluidized systems can be classified or differentiated as bubbling or circulating depending on the degree of fluidization, i.e. inflow speed of the fluidization/gasification medium. The main difference is that in the case of the circulating fluidized bed gasifier the bed material removed from the combustion chamber must be precipitated out of the gas stream by a cyclone and then recirculated into the reaction chamber.

Figure 18 shows the main principals of these systems and the relation with inflow speed of the fluidization/gasification medium.

The processes of drying, pyrolysis, oxidation and reduction take place in the entire reaction chamber and more or less homogeneously. This technology has as disadvantage the fact of a higher loading of organic contaminants, tars, and particles in the producer gas compared to fixed bed systems. About temperature levels, they must be chosen as high as possible, however, upper limits are set due the ash content and ash melting behaviour of the respective fuel. The operating temperatures for example to ligneous biomass are customarily as high as 950 °C and should be reduced to lower temperatures like 800 °C.

2.4. Solid Waste Materials

2.4.1. Introduction

The wastes, as gasification feedstock covers a wide range of materials and also mixtures. The selection of the materials to use in convert units is always an important step because the efficiency of the process depends directly on the type of unit and which kind of feedstock is being converted. The presence of a number of components in the waste such as sulfur, chlorides, and heavy metals can also vary considerably and the potential energy that we can get from the feedstock is of course an important point as well.

The size of the particles is another key parameter and typically, solid wastes in the state as received, have a highly irregular and asymmetrical lump size. Also for reasons of transport into and in the reactor, size reduction to a fine and homogeneous material is required.

Reactors like fixed-bed and moving-bed are more demanding with the feedstock and so not all the materials can be converted, in the opposite way the fluidized bed reactors has the advantage to mix sand with the feedstock which helps in the heat transfer and enables to insert more material types.

2.4.2. Waste Materials/Characteristics

Scrap tires

Approximately 30 to 33 million tires are retreaded yearly, producing a big amount of waste material which, when well utilized can be a good source of energy. Scrape tires are made of rubbery materials in the form of CxHy with some fibrous materials.

Figure 19: Scrap Tires

They have high volatile and fixed carbon contents with heating value greater than of coal. This makes it a good material for pyrolysis and chemical and energetically recovery.

This material can be pyrolysed in 4 minutes at 650 °C. The products generated are 15 – 20% gas, 20 – 30% oil, 5 – 10% water, 30 – 40% carbon black containing the main sulphur portion and other fillers and 5 – 20% steel [11].

Normally the size of the particles is: 1 – 10 mm.

Plastics/ Polymers

There are three types of waste plastics: polystyrene (PS), polyethylene (PE) and polypropylene (PP). Under pyrolysis conditions, plastic wastes can be decomposed into three fractions: gas, liquid and solid residue. The liquid products are usually

composed of higher boiling point hydrocarbons**.** In order to obtain useful gasoline-range hydrocarbons from the pyrolytic oil, fractional distillation is preferred for product separation. More valuable chemical raw materials including benzene, toluene and other condensed aromatic hydrocarbons may be obtained by refining the pyrolytic oil [12].

Figure 20: Plastic material

- **Polystyrene**

PS is a thermoplastic substance, normally existing in solid state at room temperature, but melting if heated and becoming solid again when cooling off. Pure solid polystyrene is a colorless, hard plastic with limited flexibility.

- **Polyethylene**

PE is probably the polymer we see most in daily life, is the most popular plastic in the world. For such a versatile material, it has a very simple structure, the simplest of all commercial polymers. A molecule of polyethylene is nothing more than a long chain of carbon atoms, with two hydrogen atoms attached to each carbon atom.

- **Polypropylene**

This material has the characteristic to serve double duty, both as a plastic and as a fiber. As a plastic it's used to make things like dishwasher-safe food containers. It can do this because it doesn't melt below 160 °C. As a fiber PP is used to make indoor-outdoor carpeting, it works well because polypropylene doesn't absorb water.

Generally waste polystyrene produce higher liquid, waste polyethylene and polypropylene produces higher gaseous products.

In resume, it can be said that plastics are polymers, but polymers don't have to be plastics.

Coal

In 2007, approximately 3100 million tonnes were consumed (BP 2007), what does the coal the fastest-growing fuel in the last years. This feedstock is a complex combination of materials and this combination can differ from one formation or deposit to another.

Figure 21: Anthracite and two smaller samples of Cannel coal [13]

These differences result from the varying types of vegetation from which the coal originated, the depths of burial, and the temperatures and pressures at those depths, as well as the length of time the coal has been forming in the deposit.

The varying amount of minerals in a coal deposit may also have a significant effect on its properties and classification. In addition to carbon, coals contain hydrogen, oxygen, nitrogen and varying amounts of sulphur. High-rank coals are high in carbon and heat value, but low in hydrogen and oxygen. Low-rank coals are low in carbon but high in hydrogen and oxygen content.

Anthracite is the highest carbon content, followed by bituminous, sub-bituminous and lignite coal, which has the lowest carbon content.

Normally the gases that are released from this feedstock when submitted at some conversion method are gases made up primarily of carbon monoxide and hydrogen (more than 85% by volume) and smaller quantities of carbon dioxide and methane.

Biomass

From a renewable energy perspective, biomass can be defined as: recent organic matter originally derived from plants as a result of the photosynthetic conversion process, or from animals, and which is destined to be utilized as a store of chemical energy to provide heat, electricity, or transported fuels.

Biomass resources include wood from sustainably grown plantation forests, residues from agricultural or forest production and organic waste by-products from food and fibre industries, domesticated animals and human activities [14]. The chemical composition of biomass varies among plant species, but it generally consists of approximately 50% carbon, 44% oxygen and 6% hydrogen (plus water), in the form of 25% lignin and 75% cellulose and hemicelluloses (carbohydrates). It can be said also that most species contain about 5% of smaller molecular fragments such as resins.

Biomass wastes can be divided in two groups, the first one is all the wastes that come directly from plants, woody biomass resource and the second one, materials that doesn't came from plants, non-woody biomass resource.

- **Woody biomass resource**

The source of this kind of biomass should be only from sustainably managed forest systems, forest residues or waste products.

Forest residues include the several forms of woody biomass undesirable and left over as a result of timber production and processing by the forest industry:

- *Forest arisings* are what remains after the logs have been extracted.

-*Thinnings* are generated from clearing land for forest access roads or for silvicultural operations.

- *Prunings* in forest result from removal of the lower branches.

- *Wood process residues* are produced at sawmills, pulp mills, fibreboard of the logs and timber.

- **Non-woody biomass resource**

In this type of biomass the source is not from forest, the source has different origins and they can be:

-*Agriculture crop residues* are produced in large quantities annually, this include rice husks, bagasse (this one with high potential as a biomass fuel) and cereal straw.

-*Energy crops* have been identified as having high efficiency properties; they can be converted in heat, electricity or transport fuels with very low emissions. One example is the sugar cane. These crops are grown to produce liquid fuels such as ethanol or biodiesel.

-*Animal wastes* can be used as sources of biomass for energy. The most common sources are pigs, chickens and cattle.

-*Municipal wastes* are produced in millions of tones each year and most of that wastes being disposed of in landfill dumps to produce a landfill gas, we have also industrial wastes from the food and fibre industry that can be used as biomass energy.

2.4.3. Waste Material Mixtures

It is also common the mixtures between waste materials, they can be of several types and concentrations. When two or more materials are mixed the concentration of gases will be different, the mix of those different types of gases released during the conversion can help for example in the emission reduction, one of the goals in this conversion methods. It can also improve the efficiency making a richer gas because distinctive materials can complement each other and make easier the gas synthesis.

Normally mixtures such as plastic with PET (Polyethylene Terephthalate), mixtures of plastics separated from municipal solid waste and coal with scrap tires are used.

2.4.4. Pre-Treatment Methods

There are a number of different approaches to pre-treatments and most of them involve mechanical shredding and metals removal using magnetic and electric devices. The beginning process is usually the separation of the waste materials especially when it is spoken about municipal wastes.

Shredding is the process of cut waste materials into small pieces, is an important process because the solid wastes as in the received state have a highly irregular and asymmetrical size and for reasons of transport into and in the reactor, size reduction to a fine homogeneous material is required.

Not less important is the drying process, not only for allow a smooth-flowing pneumatic transport but also to help the feedstock in his conversion process inside the reactor especially in the case of biomass that usually comes with great amount of water concentration.

2.5. Conversion Unit

2.5.1. Introduction

In the current days is important to look for some alternatives to the combustion of wastes. Those wastes when exposed to conditions of pressure and temperature previously established can be converted into a gaseous or liquid fuel with energetic potential.

The conversion unit focused here is based in the pyrolysis process which already gives proofs, in a pilot experimental pyrometer unit, that support the idea which pyrolysis is a better technology for some waste conversion. In this chapter will be explained the basic key points of the first and the second unit.

2.5.2. Old Unit

This unit was the pilot experimental unit; it is called as “Pyrotronic” and it has the layout that is shown at the figure 22 below:

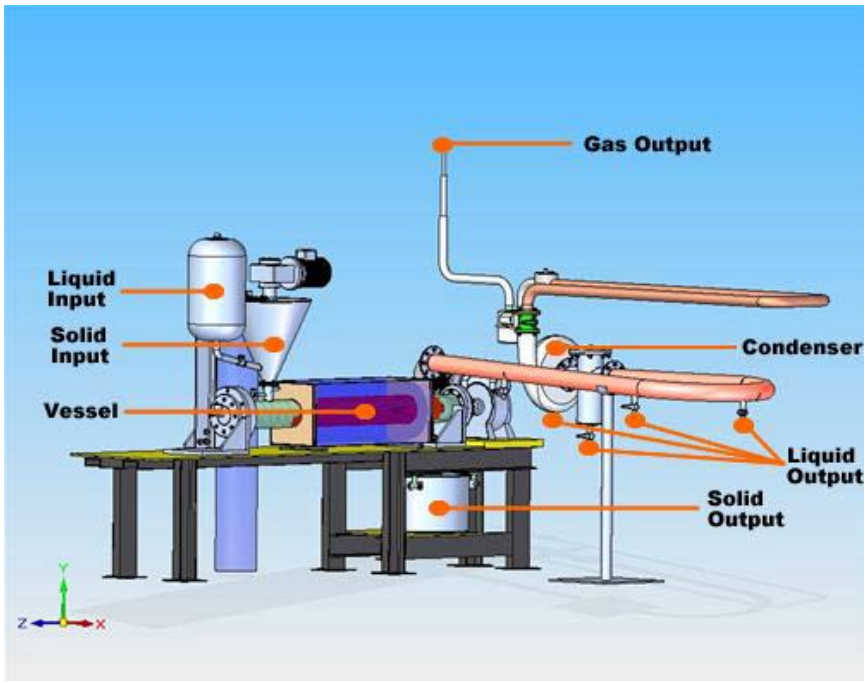


Figure 22: Layout of the experimental pyrometer "Pyrotronic"

The Pyrotronic unit consists specifically in three parts: the feeding of the material, the vessel in the reactor where occur the conversion process and the different outputs for the gas, liquid and output solid materials.

This conversion unit has a feeding system that allows the pyrolysis of liquid and/or solid products and then with a central screw, the waste materials are pushed into the hot zone, the reactor. The speed rotation of the screw controls the time of the pyrolysis with a minimum of 1 minute and maximum of 12 minutes. The reactor is provided with few electrical resistances that put the environment at the requested temperature, the temperature limit is of 650 °C in this unit.

During the conversion, gases are released without the presence of any oxidant and according to the different type of pyrolysed material the percentage of each phase will be different.

In relation to the gas flow, this will pass through a pipeline which will make some condensation of the liquid phase that can be purged in a few taps along the pipeline. The output gas is then measure with a flow-meter provide with few outputs to get some samples for off-line analysis. The output gas is conducted after the flow-meter to a burner at the end of the pipeline.

It is not possible to work at different pressures beyond the atmospheric in this unit.

2.5.3. New Unit

This new unit was not built by accident, as mentioned before the first unit, the pilot unit, had interesting results and then because of those good results was decided to go forward to a new unit, a semi-industrial unit. The new unit follows the objectives of the first one constructed but allows a bigger accuracy of results.

It's is composed by a four meters long reactor with double screw that push the waste materials through the hot zone which in this unit doesn't have resistances to warm the environment but gas burners located downdraft in the reactor. In addition the unit has another screw to pyrolyzate again the solid products.

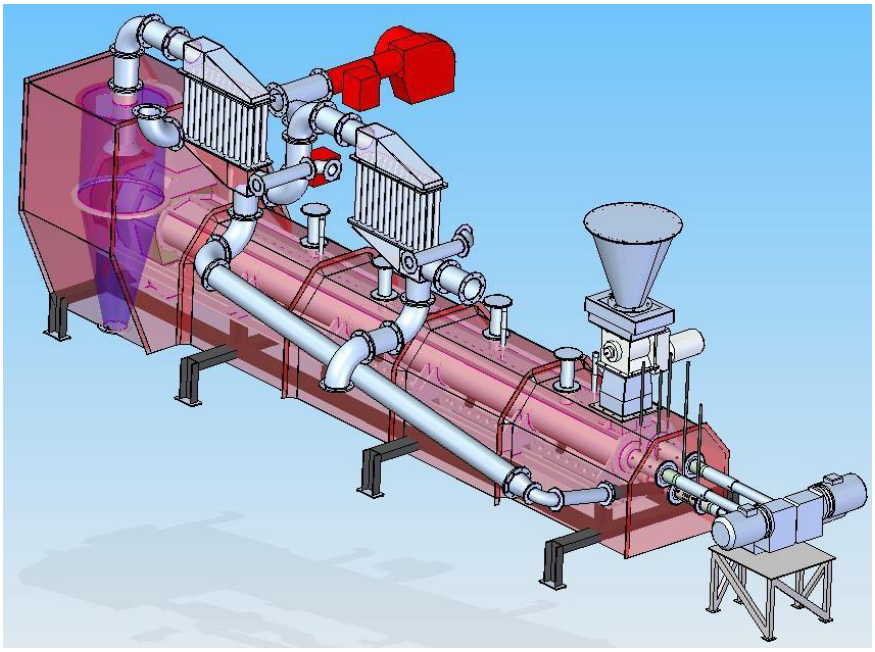


Figure 23: New Unit Layout

In figure 23 is shown one version of the new unit. Unlike the old unit this new unit let us monitoring the temperatures and pressures in every stage and even distribution of the temperature in the reactor, this is provided by thermo-cameras located in each stage. Therefore, after the pyrolysis process the gases released are guided though the pipeline into the cyclone.

The cyclone projected to this unit is shown in the following figure. It's about the cyclone and the behavior of the gases inside it that this work is focus.

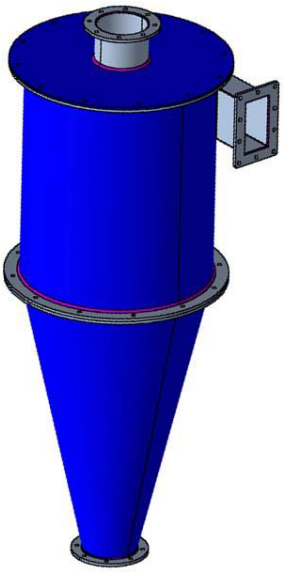


Figure 24: Cyclone of the new unit

After the gas passes the cyclone, it will go into two condensers and will continue its course till the burner situated at the end of the pipeline. Before the burner exists as well as the first unit one flow-meter to control how much gas is being produced, and also is possible to take samples of the flow during it ride.

This device was projected with the finality of separate the coarse particles from the gas stream. It has a diameter of 500 mm and height of 1508 mm.

3 EXPERIMENTAL PROCEED

3.1. Modelling Approach

The physical model of the cyclone is solved with numerical models developed for Computational Fluid Dynamics. CFD analysis involves fluid flow, heat transfer and chemical reactions.

The modelling of the cyclone can be divided in the following parts: pre-processing stage (geometry of the cyclone, mesh), setting up the models (physical and chemical properties of the gas), defining the boundary conditions based on the relation between the different measured values of the first unit, solving and post processing stage (analysis of results, comparison with experimental data).

It must be mentioned that the verification of the computational simulation is a difficult task in the real cyclone because parameters like temperature, pressure or density may be not so accurate and some errors can be associated. Nevertheless, using the experience obtained by a CFD model can significantly improve the operation of the cyclone, regarding to the good behavior of the gas and the purpose for which the cyclone was projected.

In this work, a commercial multipurpose CFD application, Fluent 6.3 developed by Fluent Ltd., has been chosen to perform the simulation.

3.1.1. Used Program

The geometry of the cyclone was programmed in the pre-processor Gambit (version 2.3) and the computational mesh was generated in the same pre-processor as well. In Gambit is also possible to insert the first's boundary conditions like where will be situated the inlet and outlet and define all the walls too. It was defined that inside the cyclone will circulate a FLUID.

3.1.2. Cyclone Model

The following figures show the developed geometry by Gambit pre-processor, this program works with coordinates and as it can be observed in the geometry, each point means one coordinate in space, therefore, all of them together will generate lines, surfaces and finally volumes. All the important measurements are in annexes.

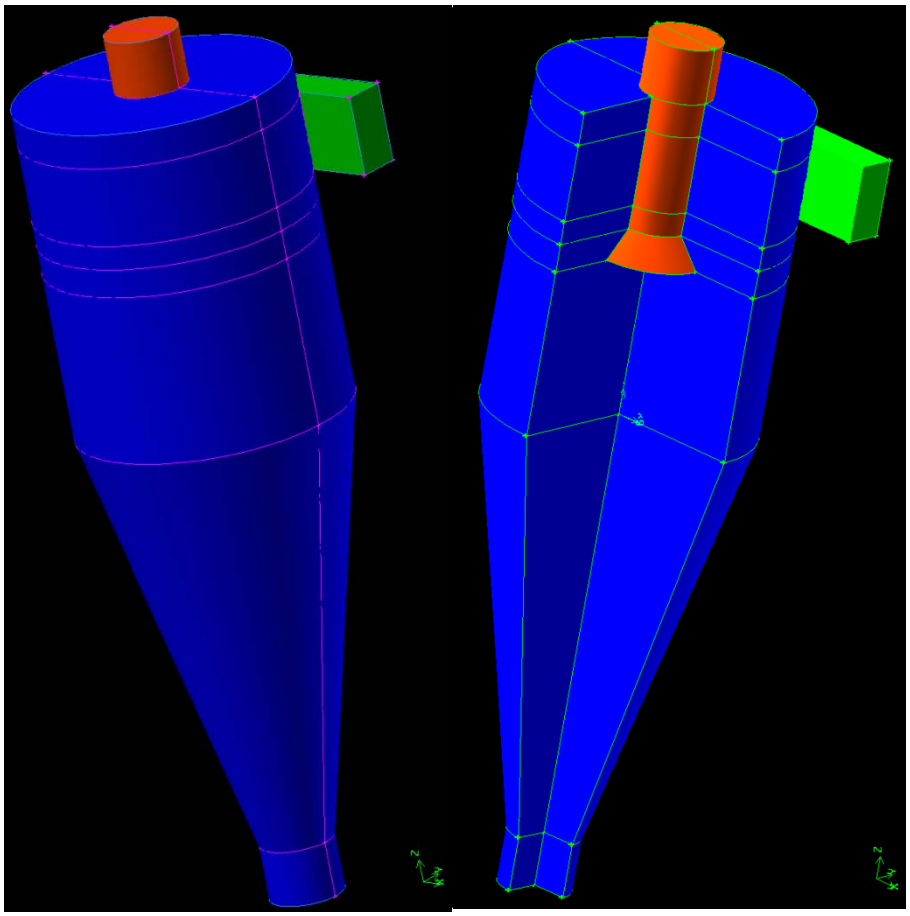


Figure 25: Cyclone geometry

But for simulations the model will be just walls not a volume in its true meaning because all the interior of the cyclone is the area of simulation.

3.2. Modelling of the Mesh

The mesh was generated in the same pre-processor used to the geometry and then saved in a mesh file. Consecutively that mesh file is open in the simulation program. The developed mesh is shown in the next figure.

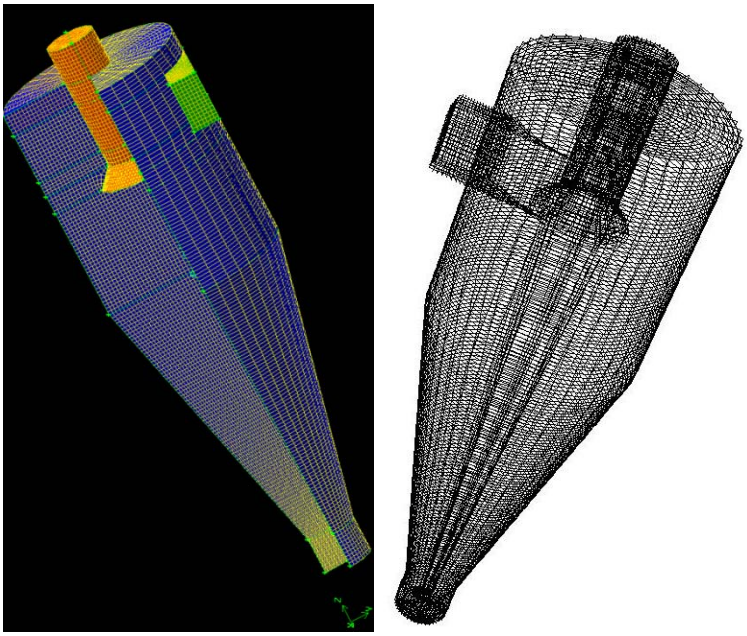


Figure 26: Pre-processor (Gambit) mesh and Fluent mesh

The mesh executed by Gambit has the following characteristics:

- **Type of computational grid-** hexahedron
- **Number of nodes-** 139054
- **Number of elements-** 120178

Gambit provides us a tool that is able to examine the mesh and so with this tool it is possible to check all the 3D elements seeing if they are in a good range of acceptable values (0 is the best value and 1 the worst). Skew should not exceed 0.85 (corresponding to 13.5 degrees). The quality of the mesh was successfully achieved; with a range 0.61 was obtained 119338 (99.30%) active elements.

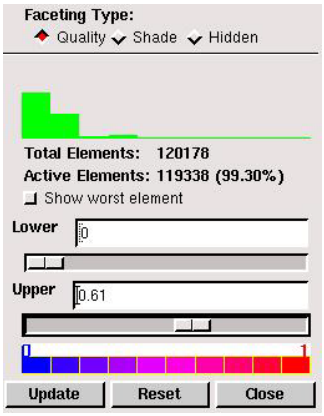


Figure 27: Mesh quality

3.3. Structuring of the Problem

At the beginning will be done a simple simulation just with one gas where an injection of small heavy particles will be also added. The chosen gas is the principal gas (Methane CH_4), commonly the gas with more mass fraction in all mixture.

This first simulation is to show in a simply away the behavior of one gas when inside the cyclone and check also if the heavy particles are really going down to the deposit bellow the cyclone.

In the second part will be executed one simulation already with all the mixture, which means a mixture composed by the six principal gases.

3.4. Simulation parameters

Physical and chemical models

A standard k-ε model and a Renormalization-Group (RNG) k-ε model were used for modelling turbulence. The standard k-ε model was used for the preliminary solution and the final calculations were performed using the RNG k-ε model. The reason for using the RNG k-ε model was that the standard k-ε model describes well flows without swirling or without sharp change within the computational region. It is necessary to use a more efficient turbulent model in case of swirling flows to enhance the accuracy. The RNG model has an additional term in its equation that significantly improves the accuracy for rapidly strained flows and also RNG theory provides an analytical formula for turbulent Prandtl numbers, while the standard k-Є model uses user-specified, constant values. While the standard k- Є model is a high-Reynolds-number model, the RNG theory provides an analytically-derived differential formula for effective viscosity that accounts for low-Reynolds-number effects [15].

It must be mentioned as well that there is no need to introduce wall functions when an RNG k-ε model is used.

It is necessary to include energy conservation equation in the set of governing equations since the simulated problem is non-isothermal, the walls of the cyclone and the fluid flow has different temperatures. This equation can be solved in terms

of temperature adding the appropriate state equation (density expressed as a function of temperature and pressure) and the constitutive relationship between enthalpy, temperature and pressure. Also in the effects of gravity (g) was taken into consideration.

Detailed theory and mathematical background is in the FLUENT manual.

3.5. Characterization of the Gas Phase

3.5.1. Mass flow calculations at inlet

The starting point for the value of mass flow was calculated based in the first unit, the unit has at the end of the pipeline one flow-meter that gives us the mass flow produced.

The provided values to the volume flow rate have a range of:

$$Q \in < 25\,,35 > \frac{m^3}{h}$$

It was assumed that the value for volume flow rate, Q, will be 31 (m^3/h). Now it is necessary to calculate the density of the mixture, this parameter will be calculated at the inlet temperature 673 K assuming a mix with six of the most present gases in the output gas, which are shown in the table below.

Table 3: Concentration of each compound in the final gas

Compounds	Concentration %
Methane (CH4)	35,70
Hydrogen (H2)	19,87
Ethylene (C2H4)	9,69
Ethane (C2H6)	8,61
Propylene (C3H6)	5,34
Carbon-dioxide (CO2)	5,24
Total	84,45

As it can be seen in table 3 the concentration is not 100% as should be, the 15,55% difference is related to the small concentrations of gases that were not taken in count and so it will be used an correction factor to put the concentration at 100%.

$$Correction\ factor = \frac{100}{84{,}45} = 1{,}184$$

Table 4: Concentration correction

Concentration %		Correction factor	Final Concentration %	Density*(ρ) (kg/m^3)	Final Density (Kg/m^3)
CH4	35,70	1,184	42,27	0,668×0,42	0,280
H2	19,87		23,53	0,082×0,24	0,019
C2H4	9,69		11,47	1,137×0,11	0,130
C2H6	8,61		10,19	1,263×0,10	0,126
C3H6	5,34		6,33	1,700×0,06	0,102
CO2	5,24		6,21	1,788×0,06	0,107
Total	84,45		100	**Density of the mixture**	0,764

*Fluent values

To = atmospheric temperature; T_{inlet} = 673 K

Table 5: Mixture densities at the inlet temperature and atmospheric temperature

	Density a T_0	Density a T_{inlet}
Density (ρ) (kg/m^3)	0,280	0,2897
	0,019	0,0362
	0,130	0,5080
	0,126	0,5445
	0,102	0,7620
	0,107	0,7970
Density of the mixture	0,764	0,3425

The mass flow rate, $\dot{m}$, is:

$$\dot{m} = Q \times \rho$$

where Q is the volume flow rate and ρ is the density of all the mixture at 673 K.

$$\dot{m} = \frac{31}{3600} \times 0{,}3425 = 0{,}00297 = 2{,}97 \times 10^{-3}\ \frac{kg}{s}$$

3.5.2. Mass fraction of the species at inlet

The chosen gas to this simulation was the gas released from the pyrolysis process of scrap tires. It was chosen this waste material because it presents one of the best values of all the waste materials studied and tested in the first unit. The table 3 shows the values of density at atmospheric temperature (300 K) and at 673 K (assumed value for the gas) as well as the values of mass fractions. The pressure considered in these values was the atmospheric pressure like at this moment the unit is working.

R= 8.31432 $\times 10^3$ $\frac{Nm}{kmol\ K}$

T_0=300K

P_0= 101325 Pa

T= 673 K

The specific gas constant, r, is:

$$r = \frac{R}{M}$$

where R is the universal gas constant and M is the atomic weight.

The value of density, ρ, is:

$$\rho i = \frac{P_0}{r \times T}$$

where P_0 is the atmospheric pressure, r the specific gas content and T the temperature which the gas is.

The density of the mixture, ρ_{mix} , is:

$$\rho_{mix} = \sum \rho i \times V_f$$

where ρi is the density of the gas and V_f is volume fraction of that gas.

Finally the mass fraction, Yi, of just one gas is:

$$Yi = \frac{\rho i}{\rho_{mix}} \times V_f$$

The mass fraction of the species is the ratio of mass of species to the total mass fraction of the mixture. The volume fraction values were obtained from measurements in the last unit.

Table 6: Mass fraction of species

	M	r	ρi	V_f	$\rho(T_0)$	Y_i
Methane (CH4)	16	519,63	0,2897	0,4227	0,6500	**0,3576**
Hydrogen (H2)	2	4157,00	0,0362	0,2353	0,0812	**0,0249**
Ethylene (C2H4)	28,05	296,40	0,5080	0,1147	1,1395	**0,1701**
Ethane (C2H6)	30,07	276,49	0,5445	0,1019	1,2216	**0,1620**
Propylene (C3H6)	42,08	197,58	0,7620	0,0633	1,7095	**0,1408**
Carbon-dioxide (CO2)	44,01	188,91	0,7970	0,0621	1,7879	**0,1445**
ρ_{mix}			0,3425		0,7682	
				1		**1**

The mass fractions results are the same at atmospheric temperature and also at different temperatures. The values that change are the values of density. After the inlet Fluent computation give us the new values of the mixture density all over the volume in study based in temperature and pressure in each cell.

3.6. Simulation with Methane/Heavy Particles

3.6.1. Boundary conditions

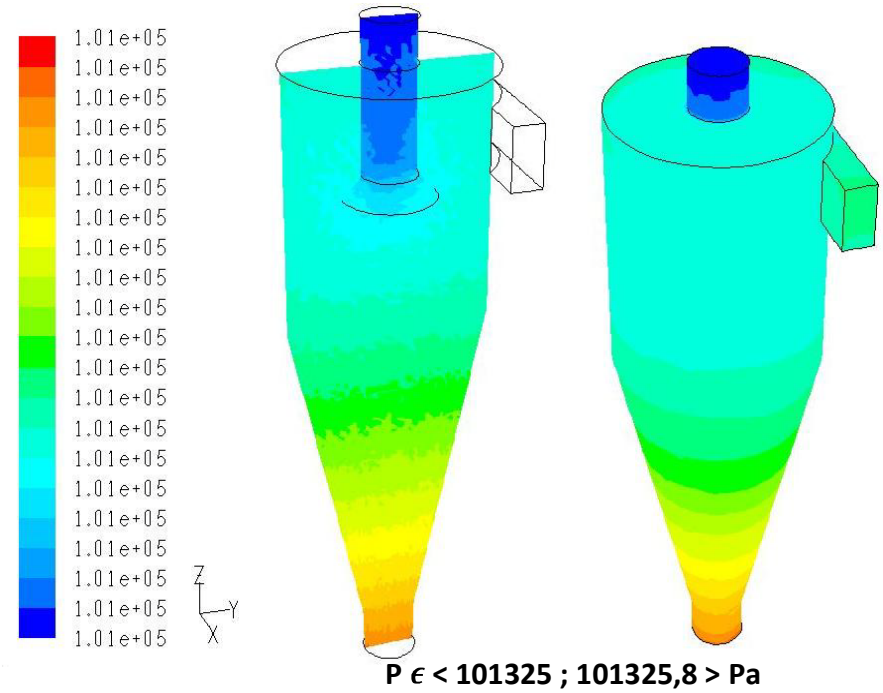
When the problem is defined in terms of the necessary equations, then the definition of the boundary conditions is required.

Inlet is defined as mass flow rate; at the beginning will be tested the mass flow provided from measurements catch on the first unit and then it will be multiplied ten times to see the differences in the behavior of the gas. The temperature of the gas is 673 K, all this simulation will be executed at atmospheric. Another boundary condition is the outlet; this one is defined as pressure outlet. The wall temperature, 573 K, is taken into account in this simulation as well as the effect of the gravity.

3.6.2. Results with real mass flow

Pressure distribution

As it shown in the figure below the distribution of static pressure seems to be not uniform but actually the pressure is constant as expected.



P ϵ < 101325 ; 101325,8 > Pa

Figure 28: Contours of static pressure for the real mass flow

In this part is used the mass flow rate obtained in the first unit, the pilot unit. It is a low value of mass flow because the new unit reactor has more than the double size comparing to the reactor of the pilot unit, therefore the quantity of gas released from the pyrolysis process that enter in the cyclone should be bigger than the first and as consequence highest value of mass flow.

Velocity distribution

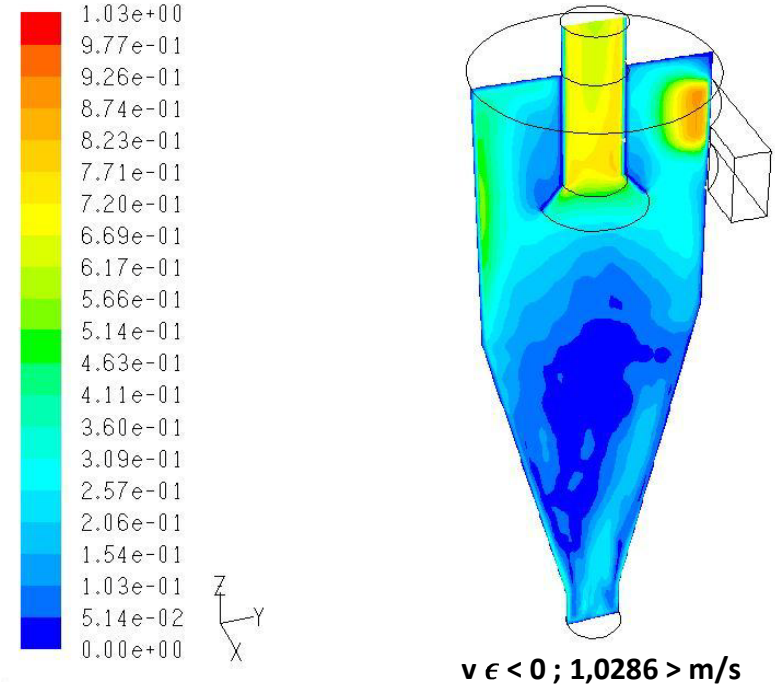


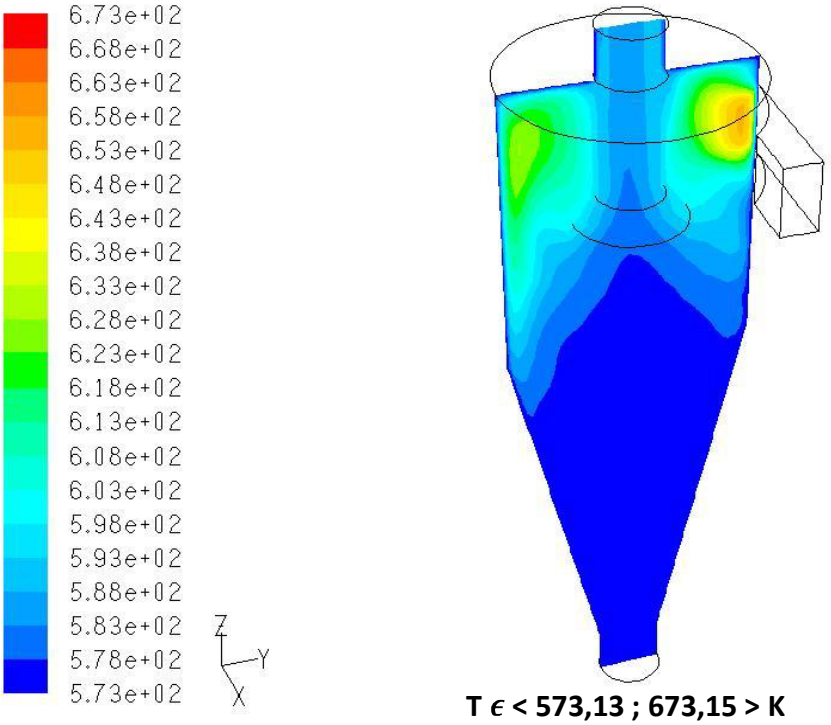
Figure 29: Contours of static velocity magnitude 1st case

The velocity magnitude is not high as foreseen; it can be observed by the previous figure that the maximum values of velocity is at the inlet and in the pipe that leads the gas to the outlet which are sections with less area and consequently with higher velocity then the rest of all the cyclone volume. The lower region of the cyclone has velocities close to 0 m/s and in some regions really zero because this part of the cyclone geometry is considered the repose area where the velocities are quite smaller and let the heavy particles land.

In appendix A are shown figures with the results of contours in X velocity, Z velocity and tangential velocity. It can be observed by the contours of X velocity that exist positive and negative velocities, this is depending in which direction the flow is

circulating inside the cyclone comparing to the X axis. As it shown in figure A 1 the velocity in agreement with X has the maximum at the inlet, area with less value and the starts to decrease when goes inside the cyclone and has more area to occupy. In figure A 2 happens the same but not at the inlet but at the outlet where the gas has to go out in direction o Z. Figure A 3 shows us the tangential where it can be seen that the lowest value is at the middle of the cyclone.

Temperature distribution



T ϵ < 573,13 ; 673,15 > K

Figure 30: Contours of static temperature 1st case

The temperature distribution for this case shows that for velocities close to 0 m/s or even zero the cooling effect is higher because the gas will stay more time in contact with the walls and the convection will be higher therefore the temperature is almost the same as the wall in the lower part of the cyclone. As expected the high values of temperature are in the upper part of the geometry.

Density distribution

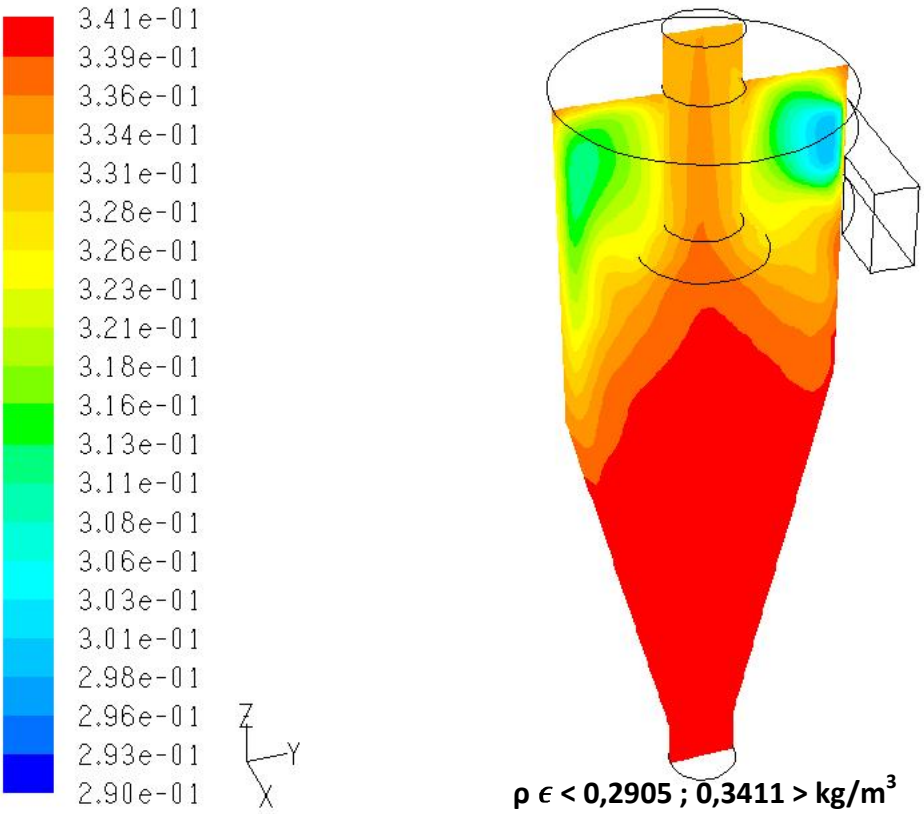


Figure 31: Contours of density 1st case

When the cooling effect in the gas is higher like in this case it can be noticed that where the temperature has the lowest values the density of the gas will be higher therefore this distribution where at the inlet has the lowest value and the bottom of the cyclone the opposite.

Path lines of the flow

The next figure shows the results of path lines of this simulation. According to the previous results the behavior of the gas inside the cyclone was expected as a non well formed behavior like it show in figure 32 because the path lines don't have a good trajectory in all the volume, actually they are disorderly at the lower part because of the lower value of velocity.

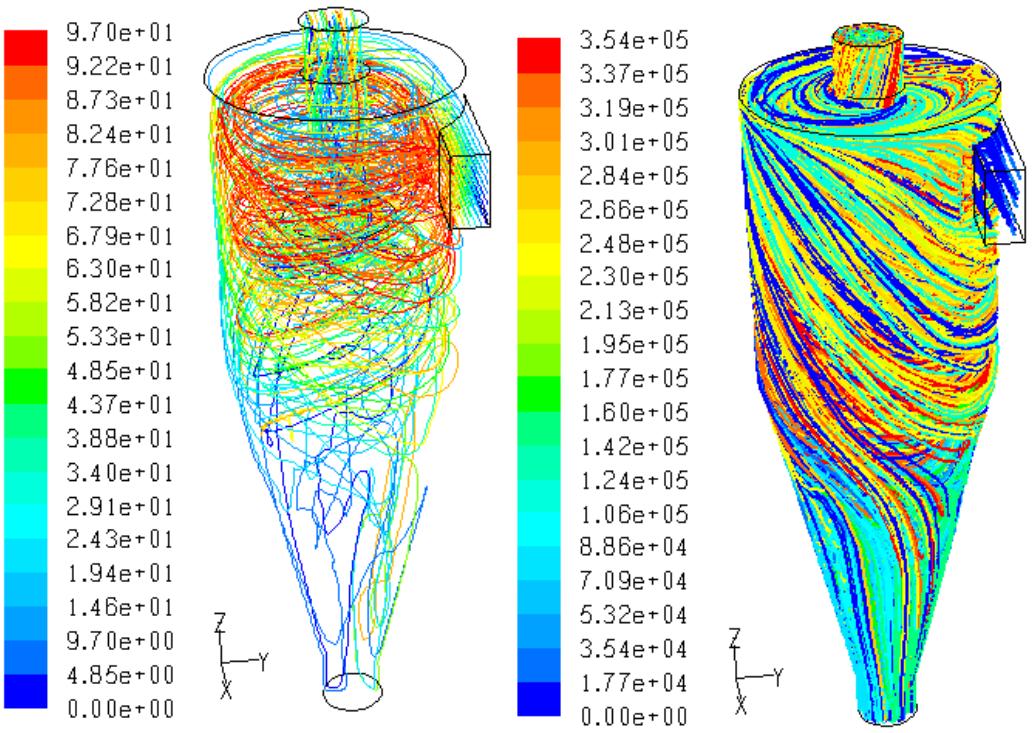


Figure 32: Path lines at the interior of the cyclone for the real mass flow

It can be seen in the figure above at the right that at the inlet and in the upper region of the cyclone the gas has at the beginning a normal trajectory but since the gas starts to lose velocity the path lines start to be not so well-behaved as shown in the left figure.

Particles traces

The particle tracks provide another view on the situation inside the cyclone and help us to understand better what going on inside.

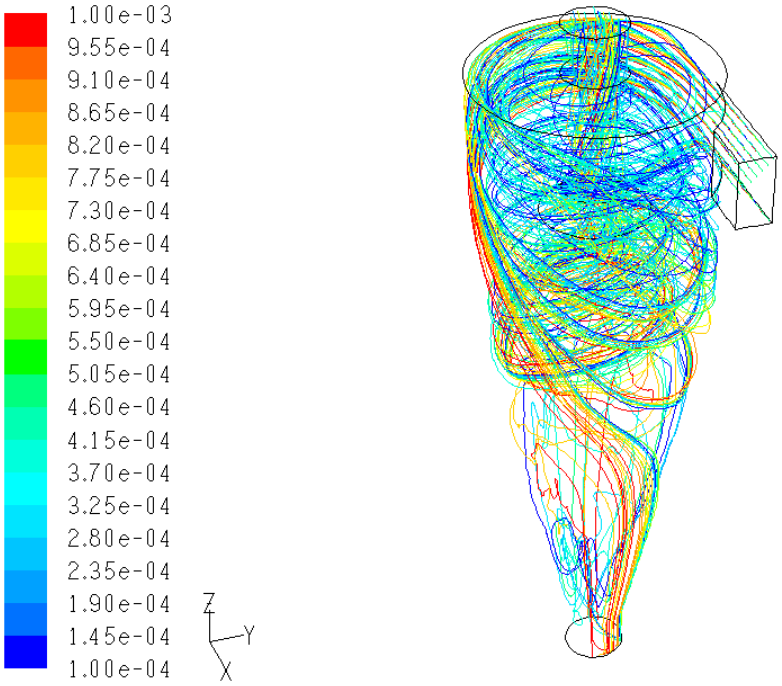


Figure 33: Particles traces colored by diameter for the real mass flow

The particles traces for this case have a strong recirculation because of the lowest values of velocity in the lower part of the cyclone. Nevertheless the dust and the heavy particles are going down to the deposit under the cyclone as it can be observed in figure 33. It is necessary to take into account that the particles have a certain residence time; in this case they have a long residence time (close to 100 sec) depending on the trajectory. If particles are in the area where it is possible to reach the bottom of the cyclone they will go directly to the box otherwise they will remain a bit longer and possible will go up to the outlet to a possible after filtration. For this case there is no problem with ash melting in the walls because the level of the temperature doesn't achieve that point.

3.6.3. Results with higher mass flow

Pressure distribution

This simulation was also executed at atmospheric pressure however the mass flow is higher therefore variations will happen inside the cyclone.

As it shown in the figure below the distribution of static pressure has more sense in this case, the contours indicate small variations with the maximum at the inlet and once inside the cyclone start to decreasing till the outlet which is the minimum.

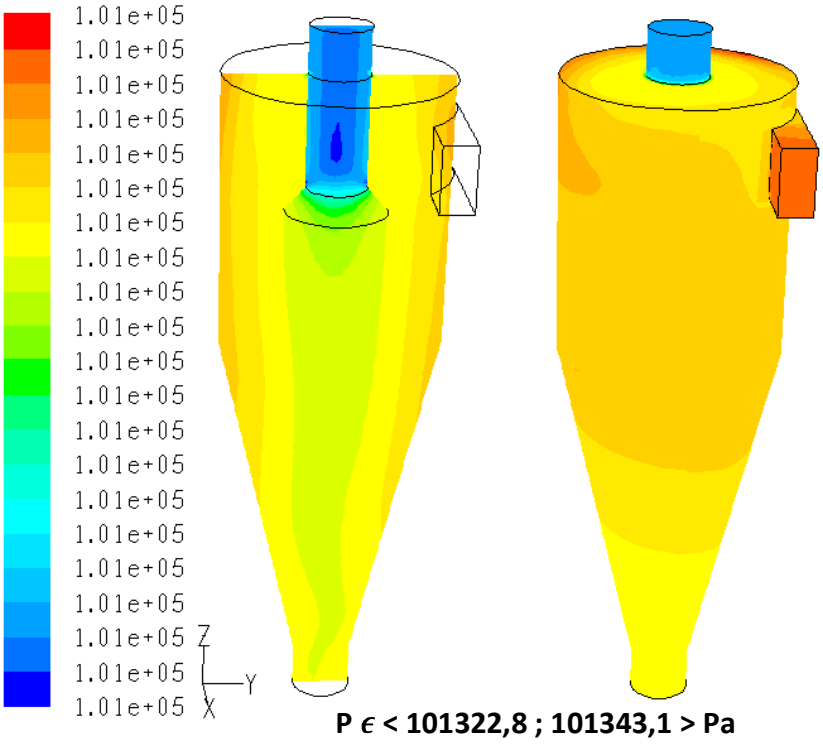


Figure 34: Contours of static pressure for higher mass flow

It was also noticed that in this case the computation by Fluent was easier than in the first case because with a higher value of mass flow as a boundary condition for inlet the iterations went more quickly to a convergence.

Velocity distribution

Contours of velocity in figure 35 shows what was expected, the velocity has higher value and a better distribution. The maximum values of velocity are at the inlet and in the pipe that leads the gas to the outlet and as well as the previous case the lower region of the cyclone has the lower velocities.

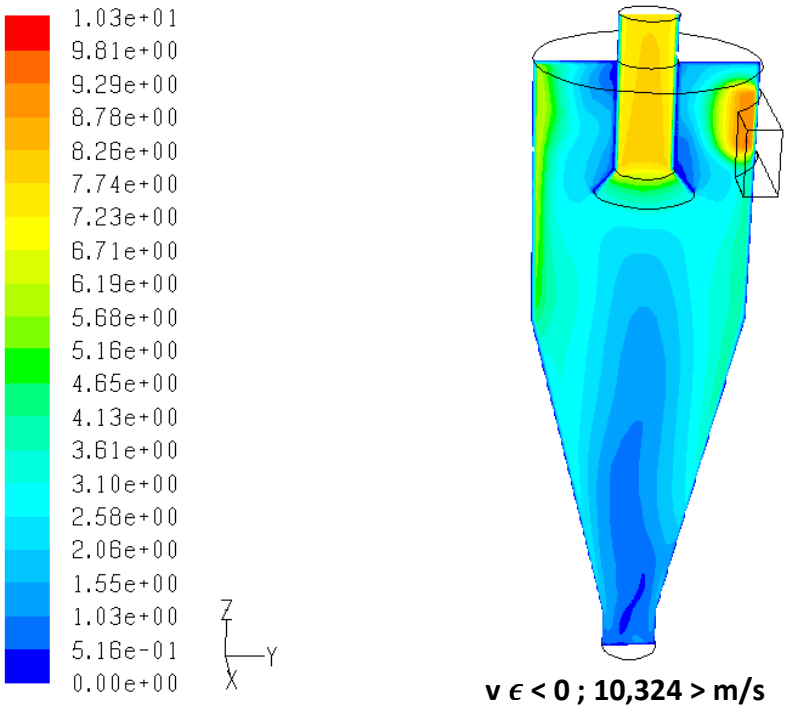


Figure 35: Contours of static velocity magnitude 2nd case

Close to the outlet ash it can be seen that the velocities are almost zero which means the fluid is stagnant and the heavy particles are going down because there is no effect of the velocity just the gravity effect. Figure B 1 and B 2 in appendix B demonstrates also better results in X velocity as well as the velocity according Z axis. Tangential velocity has much better results as it present in figure B 3. The contours of tangential velocity display that in the middle of the cyclone the values are close to zero which means that the flow is really going up.

Temperature distribution

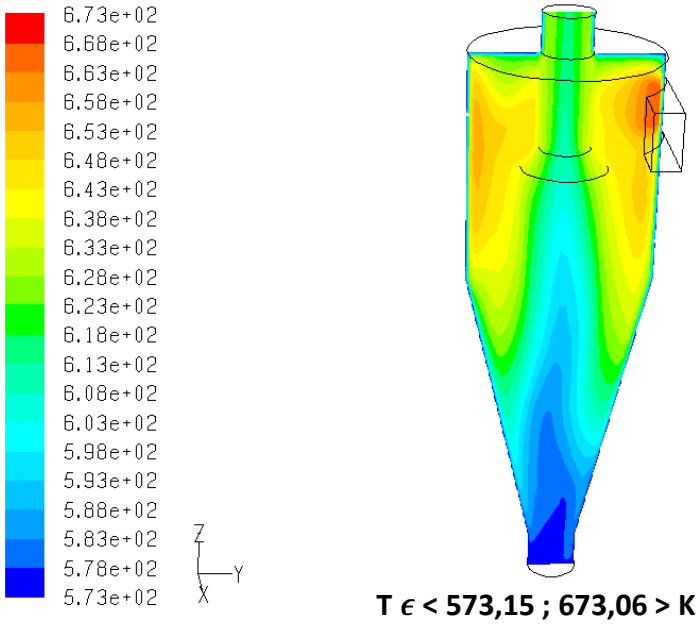


Figure 36: Contours of static temperature 2nd case

The temperature distribution for this case has also good behavior that's because of the fact that a higher velocity doesn't let the gas to cool more quickly, in other words the gas will not suffer so strongly the cooling effect of the walls. The maximum and minimum values are situated also at the same parts as the previous case.

Density distribution

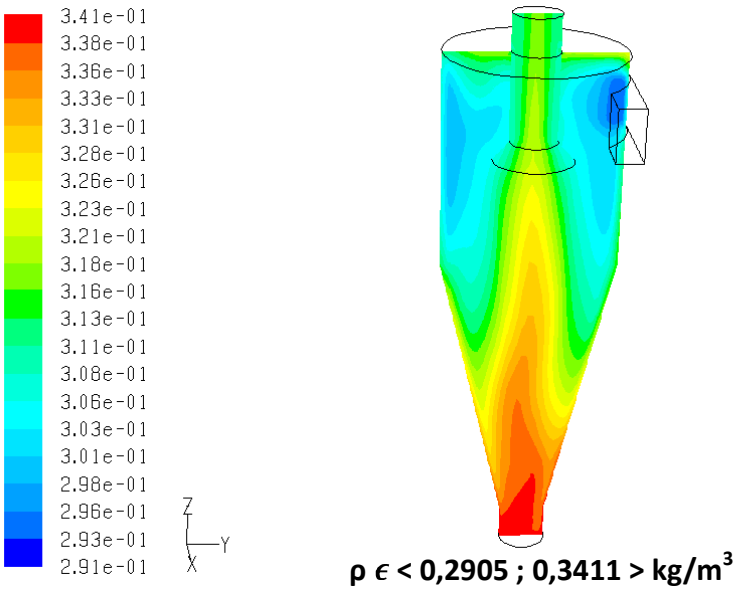


Figure 37: Contours of density distribution 2nd case

As expected the density in the case of a higher mass flow doesn't suffer so big changes like in the in the 1st case where the cooling effect caused by the walls is more noticed.

Path lines of the flow

There is no doubt about the influence of a good set of parameters to do a simulation as it can be seen by the figure below.

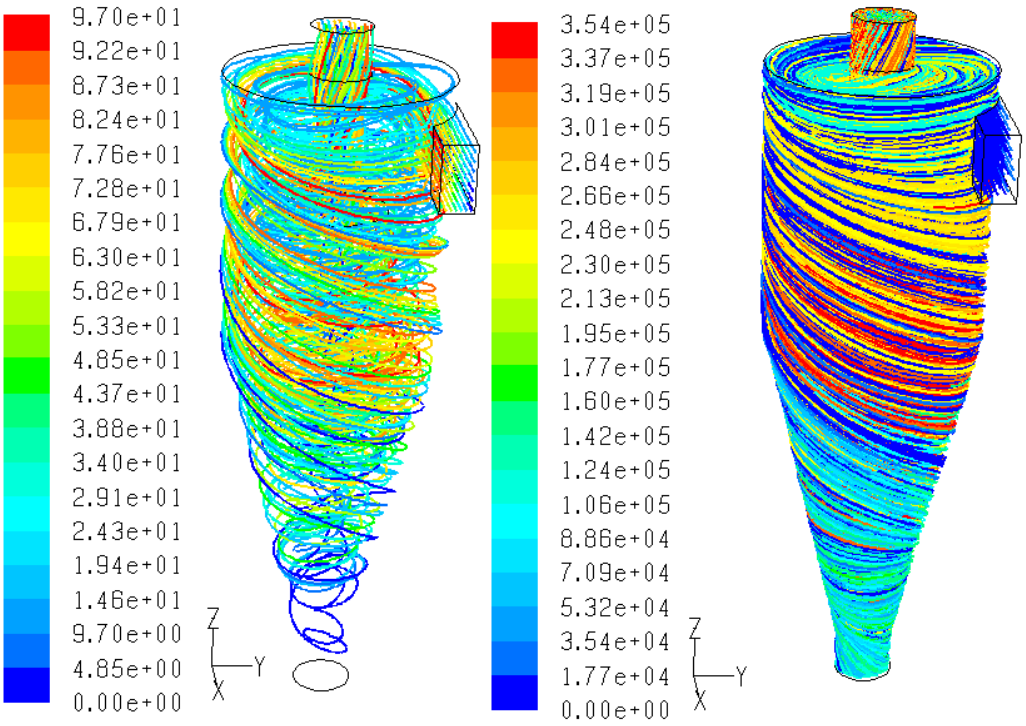


Figure 38: Path lines at the interior of the cyclone for higher mass flow

The path lines for this second simulation show us the good behavior of the gas inside the cyclone where the gas goes around the walls in direction to the bottom releasing that away the undesirable dust and heavy particles. In figure 38 is shown a good perspective from that path lines from the inlet and also in all the interior of the cyclone.

Particles traces

As expected the particles traces for this second case prove what have been said previously. The particles traces for this second case are better formed and they are going orderly to the outlet ash without too much recirculation as shown in figure down.

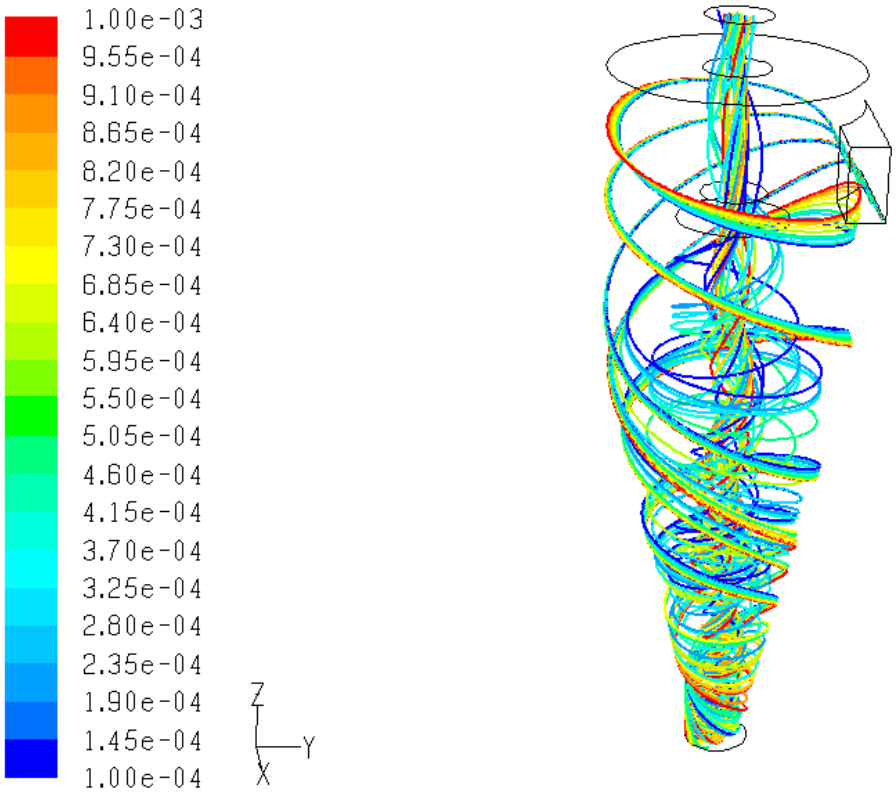


Figure 39: Particles traces colored by diameter for higher mass flow

The residence time for the particles in this simulation was 27 s at maximum because the gas flow has enough velocity to transport the small particles till the bottom of the cyclone more quickly than with a low velocity as the case focus previously. Particles with bigger diameter (red traces) will go first to the outlet ash as shown in figure 39.

3.7. Simulation with all Species

Once it was already observed that the behavior of the gas would be better with higher mass flow this simulation was executed with the same mass flow as the 2nd case and without injection of heavy particles to turn the simulation more easier to get, despite that it can be assumed that the behavior of the heavy particles will follow the same behavior like in the second case.

Pressure distribution

The contours of static distribution shown in appendix C figure C1 shows almost the same distribution like in the 2nd case where the highest value is at the inlet and the lower in the outlet.

Velocity distribution

The velocity will be also similar to the second case but because it's a composition of different gases (6 species) and not just one like methane in the second case the velocity of the gas inside the cyclone will decrease a little bit.

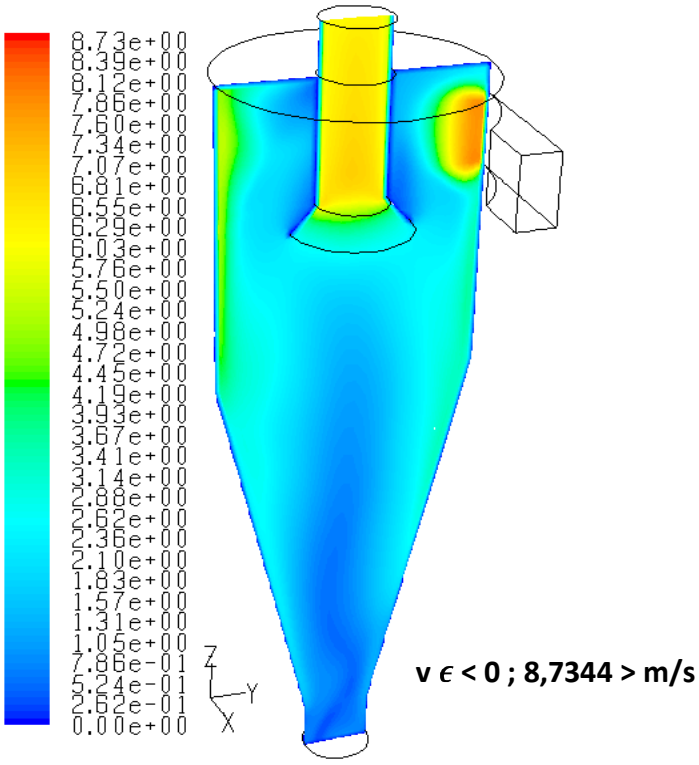


Figure 40: Contours of static velocity magnitude 3rd case

That decrease of velocity is caused because of the different values of density, methane at inlet temperature 673 K (400 °C) has less value of density comparing to all mixture in this 3rd simulation at the same temperature.

Temperature distribution

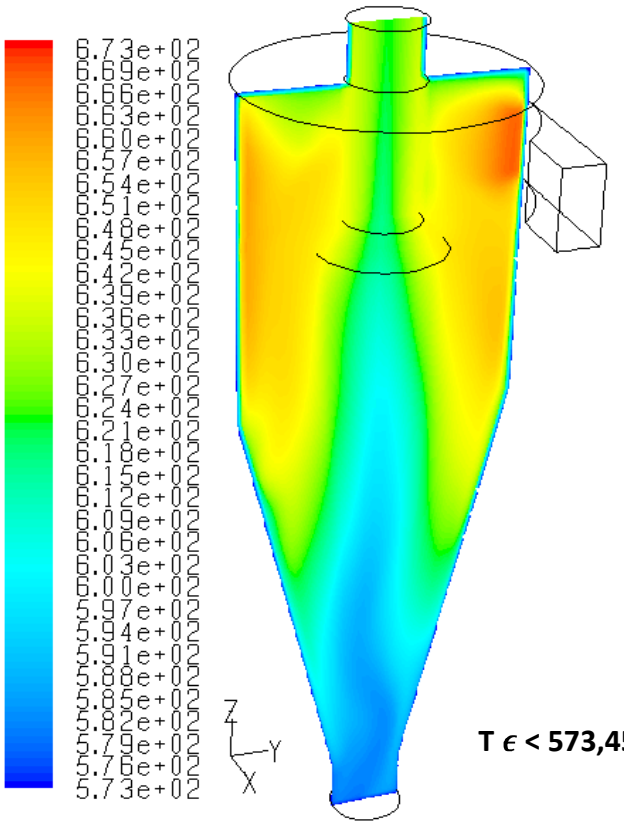


Figure 41: Contours of static temperature 3rd case

The temperature distribution is also similar to the second case despite that in this case the lower value is a little higher as it shown in contours of the figure 41. The lower values in this cross section are like in the other case in the lower part of the cyclone, in the bottom, but here the lower part isn't colored by dark blue like in the 2nd case.

Density distribution

The density distribution for the case of the mixture of six species have the behavior like in the first and second case as well with high and low values of density situated in the places where are low and high values of temperature as it can be observed in appendix C figure C5 .

Species concentration

In table 7 can be seen the mass fractions of all the species in this gas in a global range, the mass fraction of a specie means the mass of a specie per unit mass of mixture (kg of species in 1kg of the mixture). The mass fraction of the six species that were established at the beginning doesn't change too much; the distribution of all of them is shown on appendix C in figures C6, C7 and C8. Here is presented the distribution of mass fraction about methane, the gas with more concentration in the output gas.

Table 7: Mass fraction in global range

Compounds	Mass fraction (Y_i)
Methane (CH4)	< 0,3389 ; 0,3680 >
Hydrogen (H2)	< 0,0081 ; 0,0262 >
Ethylene (C2H4)	< 0,1694 ; 0,1755 >
Ethane (C2H6)	< 0,1604 ; 0,1686 >
Propylene (C3H6)	< 0,1391 ; 0,1521 >
Carbon-dioxide (CO2)	< 0,1409 ; 0,1568 >

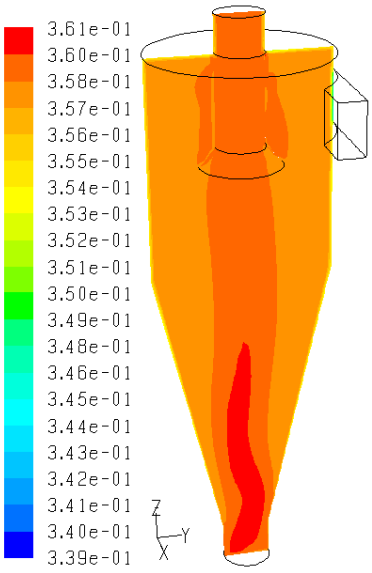


Figure 42: Mass fraction of ch4

Species mass fraction indicates the percentage of mass of particular specie present at certain point or plane. In the figure 42 the higher values of mass fraction are distributed along the middle part of the cyclone as well as the rest of the species shown in appendix C.

Path lines colored by velocity

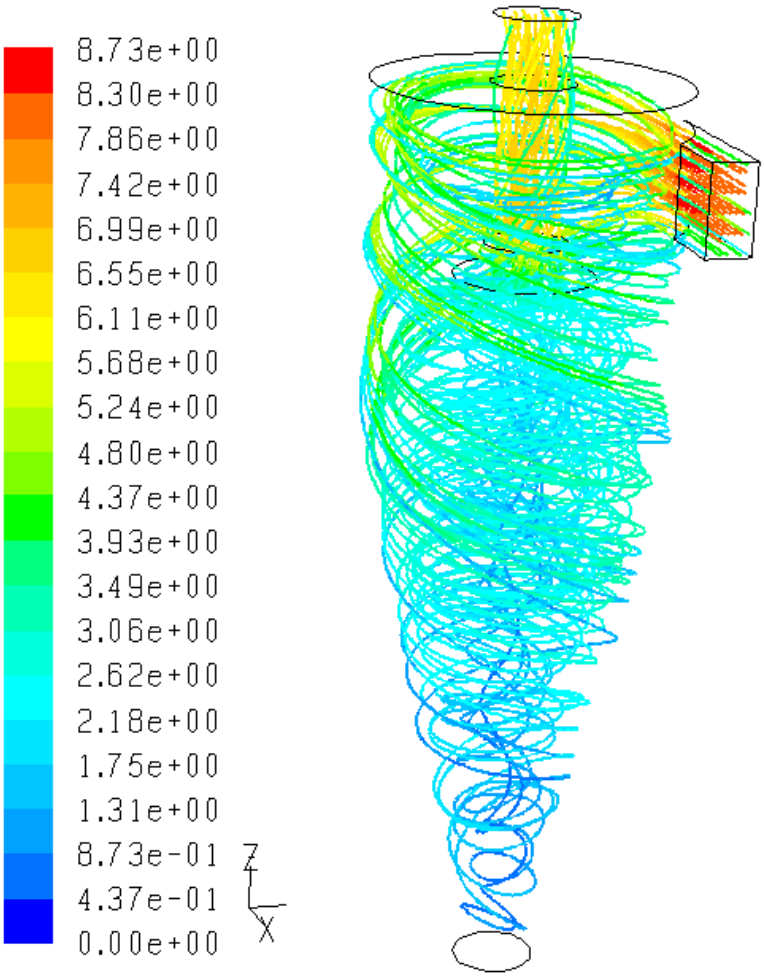


Figure 43: Path lines colored by velocity value 3rd case

Figure 43 shows the path lines of the mixture and as it can be observed the behavior of the lines is good as well as the behavior of the velocity which has the higher value at the inlet and once inside starts to decrease the value of velocity till zero in the lower part of the cyclone releasing that form the dust material and heavy particles presented in the flow.

The heavy particles will describe the same trajectory once the flow has enough energy to transport the heavy particles to the box under the cyclone.

4 DISCUSSION OF THE RESULTS

The calculation has been performed on a Microsoft Windows platform (Windows XP) with an Intel (R) Core 2.16 GHz processor and 1.99 GB of RAM. The post-processing tools of the FLUENT 6.3 code have been used for the examination of the results; all the simulations were executed with the parameter double precision and stopped were the convergence was obtained.

The results show us a big discrepancy in the behavior of the gas when it is increased the value of mass flow. The following figures show that difference between the real mass flow (1st case) used in the unit and a mass flow ten times higher (2nd case) in case of temperature and density distribution.

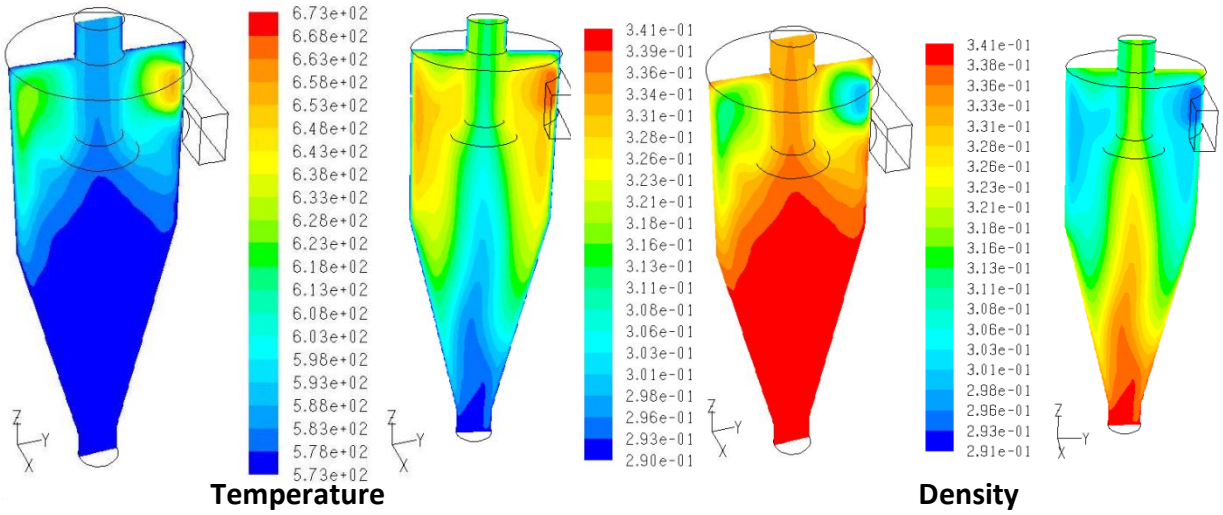


Figure 44: Distribution of the temperature and the effect in the density

It can be seen by the last figure the influence of a higher mass flow, a higher mass flow induce higher value of velocity and so different distribution of temperatures and density as well. The temperature when with a lower value causes the opposite effect in the density, in other words higher density.

The condensation effect observed in the conversion unit in the first test can be caused by this problem focused here, where for the real conditions of mass flow the time that the flow takes to get out from the cyclone is high therefore convection will take place with the walls of the cyclone and changes in the gas will occur like phase change caused by the abrupt cooling.

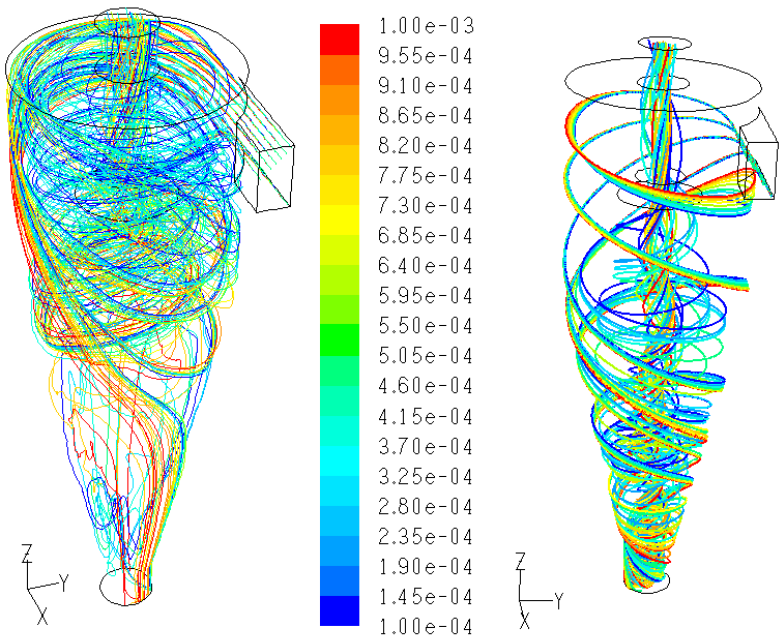


Figure 45: Particles traces comparison for the 1st and 2nd cases

The some can be said about the particles traces by analyzing the last figure where is shown the particles traces colored by diameter. At the left the 1st case with the real mass flow and at the right the 2nd case with ten times higher mass flow. In both cases the particles are going to the outlet ash but in the second case the residence time of the particles is not so high and with better trajectory therefore the particles will go first to the outlet ash.

The 3rd case is similar to the 2nd case where the mass flow has the same value and so the same behavior inside the cyclone in study. The parameter that suffers a small change is the velocity that decreases a little bit comparing to the second simulation, that's because of a different value of density that the mixture has.

5 CONCLUSIONS

The conclusions taken over the work say us that at first the mass flow that the conversion unit is working at the moment is not appropriated for the volume of the cyclone therefore the behavior of the gas is not good and as consequence of that the velocity, temperature, density distribution as well as the path lines of the gas don't have good distribution and conduct inside the cyclone. When was tested a second mass flow ten times higher was observed better behavior of the gas, the velocity distribution for the real mass flow (figure 29) was non-uniform and with a lot of standing regions which makes that the gas will suffer more stronger the cooling effect caused by the walls of the cyclone (figure 44) which are not at the same temperature as the gas.

The temperature cause direct changes in the density of the mixture and so like it was noticed the lower part of the cyclone is the most problematic part because it's the part that the gas takes more time to get out therefore the higher values of density in that region. In the unit same problems of condensation were observed and that can be because of the high values of density caused by the quickly cooling effect in the output gas in the lower zone of the cyclone therefore the gas suffer a possible phase change and same liquid will go to the box under the cyclone.

The path lines of the gas provided (figures 32, 38 and 43) by the simulation shows us the big differences of using a higher or lower value of mass flow, in figure 32 can be seen that the gas is not so ordered special in the bottom of the cyclone by other hand in the 2nd case with ten times higher mass flow the behavior of the gas is good and well formed as it shown in figure 38 as well as the 3rd case for the gas mixture with the six species chosen previously. Like the path lines of the gas the particles traces of the heavy particles had a good behavior with higher value of mass flow but it has to be said that if the value of mass flow will be too much high the velocity will increase a lot as well and the heavy particles will not suffer so quickly the gravity effect.

Despite everything the dust materials/ heavy particles are going to the outlet ash as wanted and as was the purpose of its construction.

6 SOLUTIONS/ SUGGESTIONS

The first and important suggestion is to provide more mass flow to the cyclone but considering the work conditions of the conversion unit that will not be so easy to get because to get more quantity of gas the reactor has to be capable to produce more gas from the pyrolysis of the waste materials which means fed the reactor with more material and increase the speed of the central screws however there is the possibility that the waste material will not be utilized efficiently and will get out from the reactor still with energy inside it, therefore a possible solution is to use a small cyclone.

The second suggestion is to try to get uniform temperature across the cyclone because the temperature together with low mass flow will change the properties of the gas in a way that is not wanted. For this it can be used resistances around the walls of the cyclone and use a better isolation system. In this case is normal to use fiber glass material that has a high thermal isolation property.

For Fluent is complicated to iterate between too similar values like for example when the pressure doesn't change too much and so the iteration will take strange values sometimes going to a divergent solution so a good range of boundary conditions are required and important to get better and easier simulation and parameters like wall temperatures, mass flow at the inlet should be known accurately.

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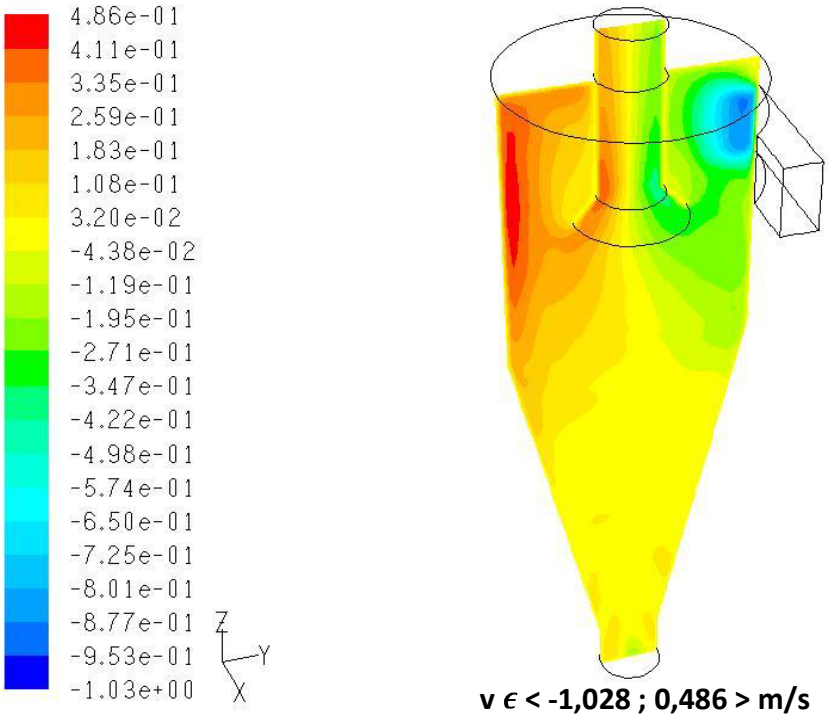
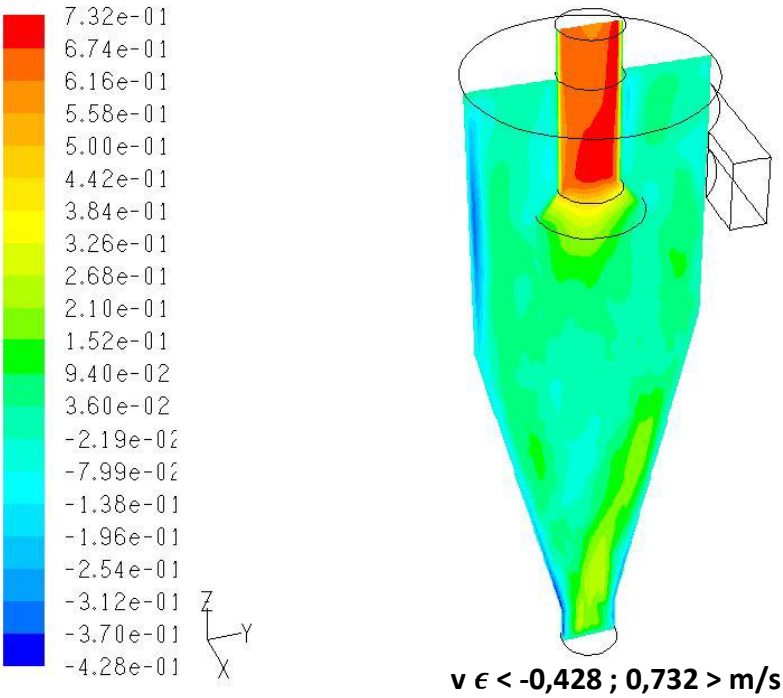
8 APPENDIX

8.1. Appendix A



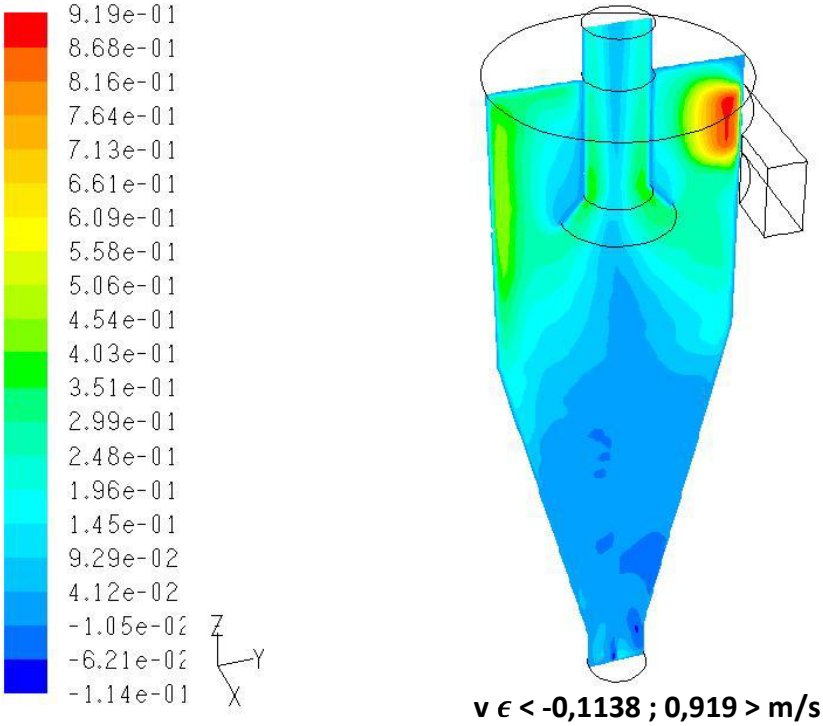
v ϵ < -1,028 ; 0,486 > m/s

Figure A 1: Contours of X velocity 1st case



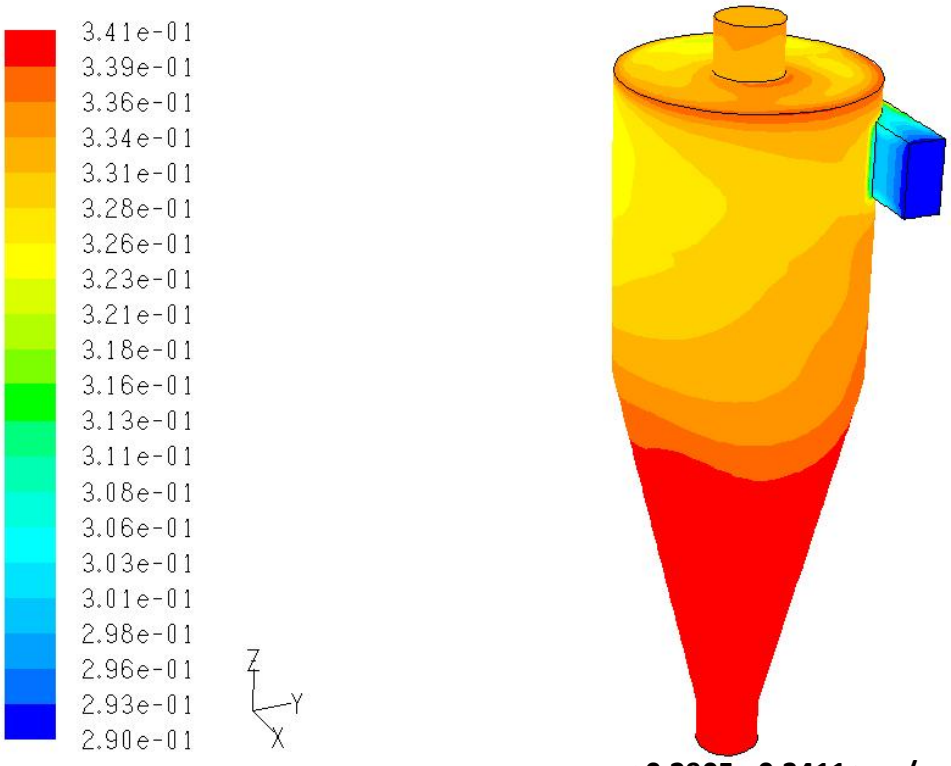
v ϵ < -0,428 ; 0,732 > m/s

Figure A 2: Contours of Z velocity 1st case



v ϵ < -0,1138 ; 0,919 > m/s

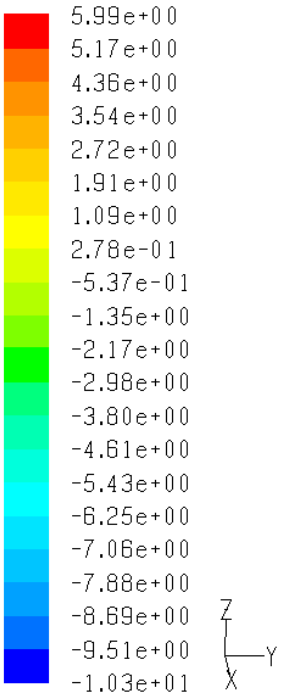
Figure A 3: Contours of tangential velocity 1st case

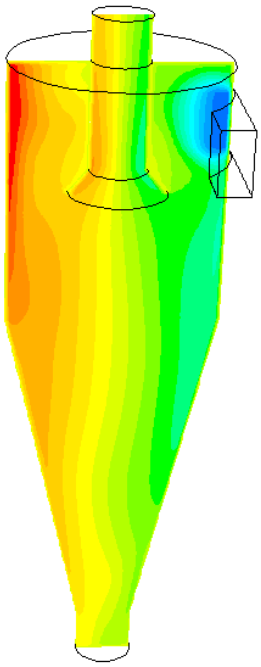


ρ ϵ < 0,2905 ; 0,3411 > m/s

Figure A 4: Contours of density in walls 1st case

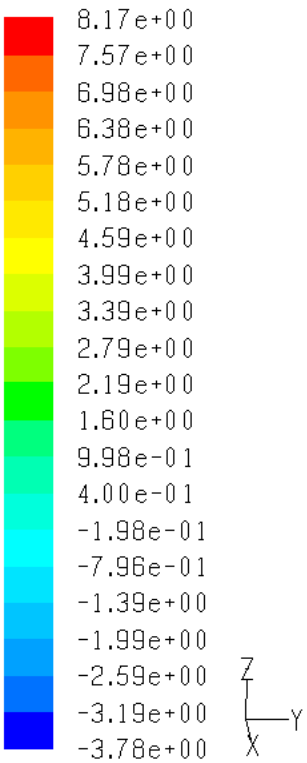
8.2. Appendix B

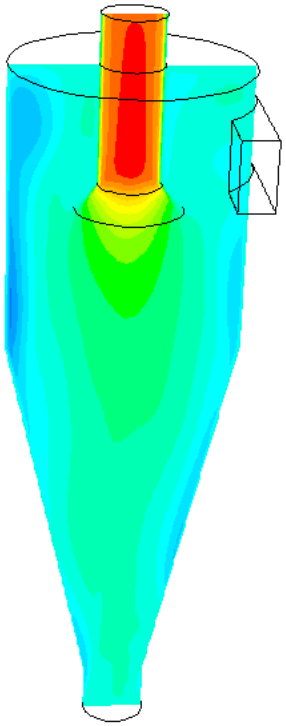




v ϵ < -10,323 ; 5,986 > m/s

Figure B 1: Contours of X velocity 2nd case





v ϵ < -3,785 ; 8,172 > m/s

Figure B 2: Contours of Z velocity 2nd case

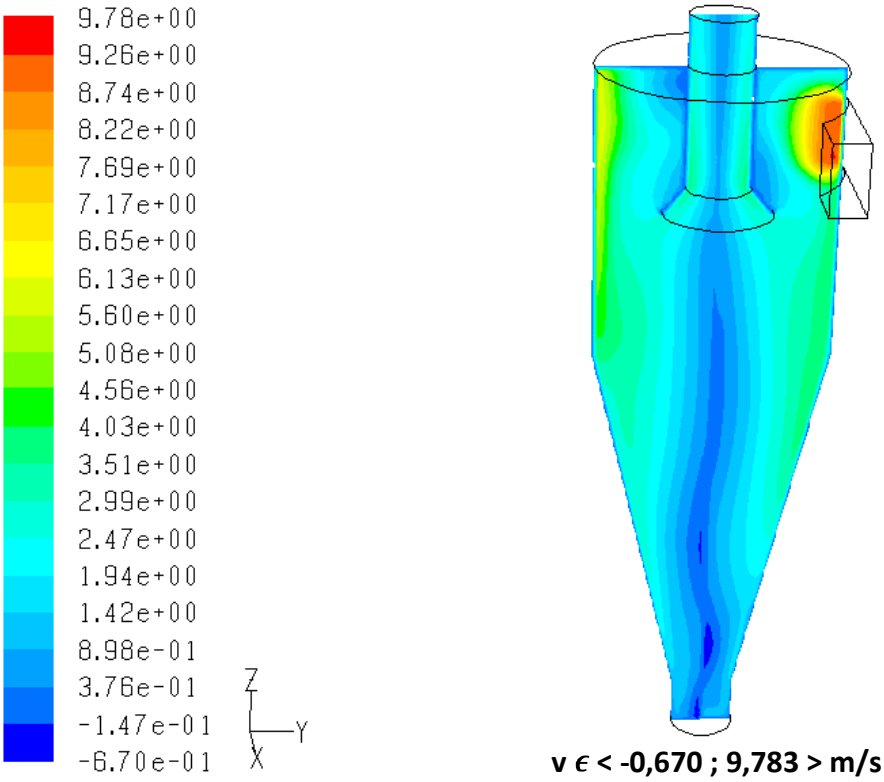


Figure B 3: Contours of tangential velocity 2nd case

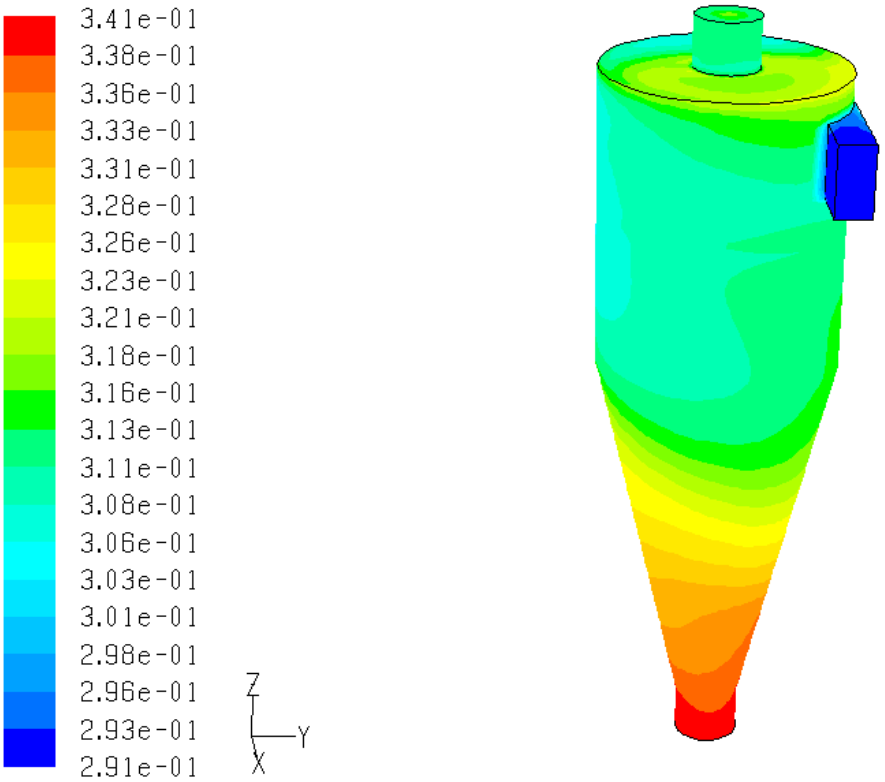
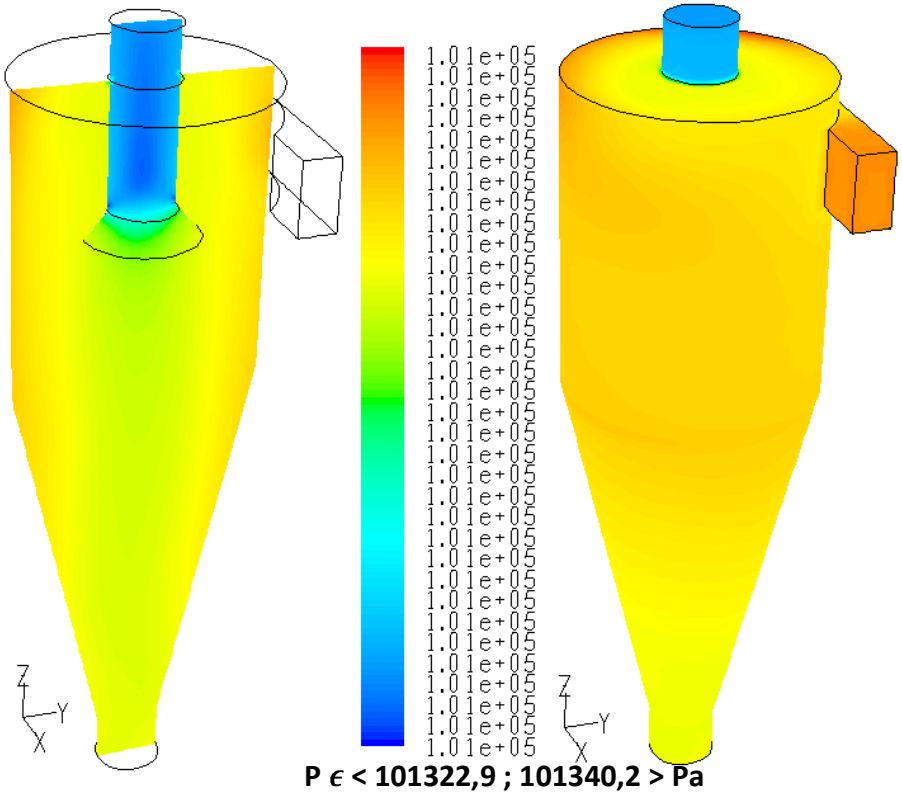


Figure B 4: Contours of density distribution 2nd case

8.3. Appendix C



P ϵ < 101322,9 ; 101340,2 > Pa

Figure C 1: Contours of static pressure 3rd case

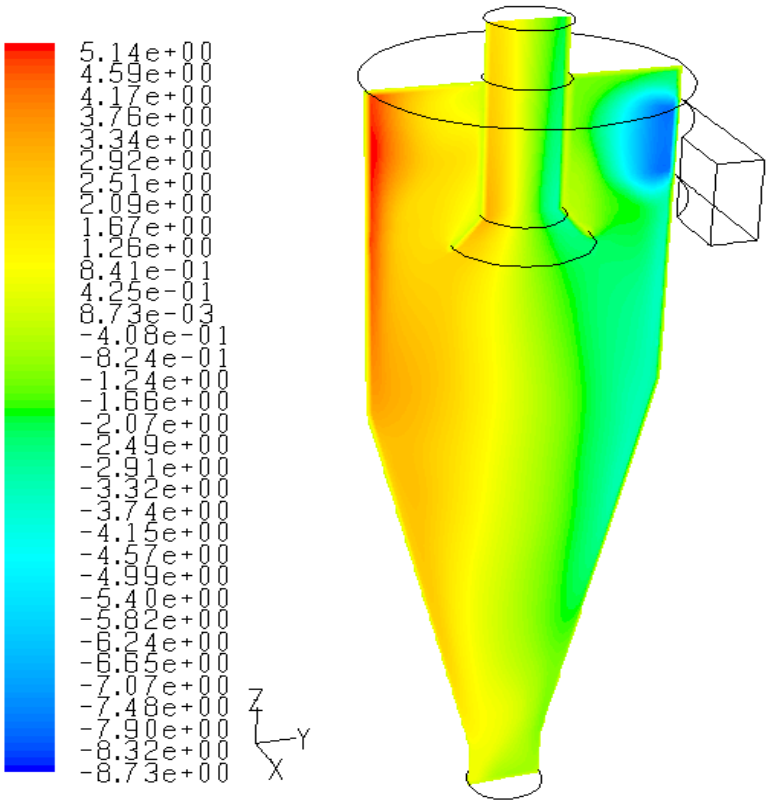


Figure C 2: Contours of X velocity 3rd case

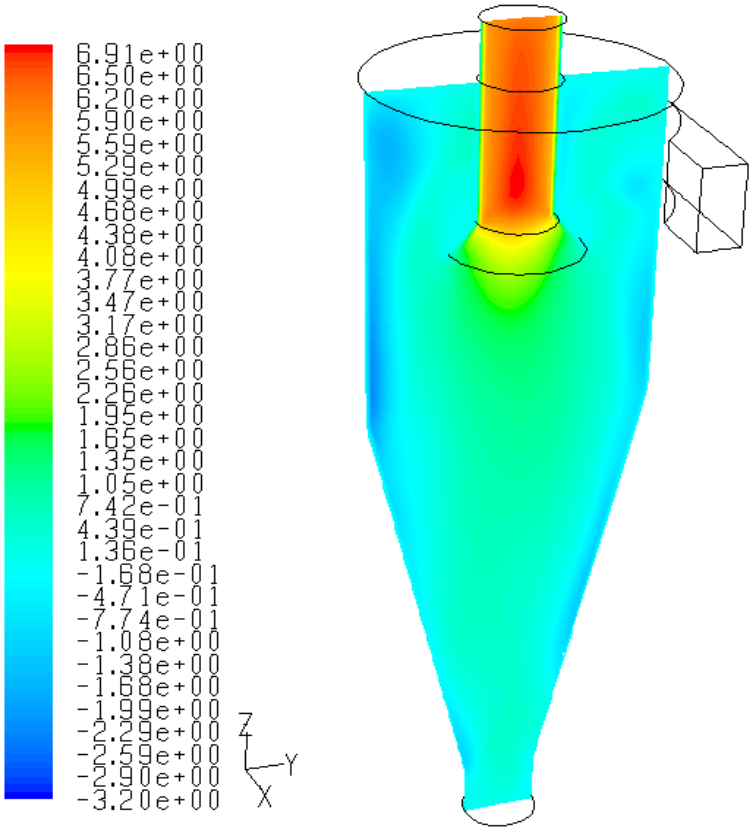


Figure C 3: Contours of Z velocity 3rd case

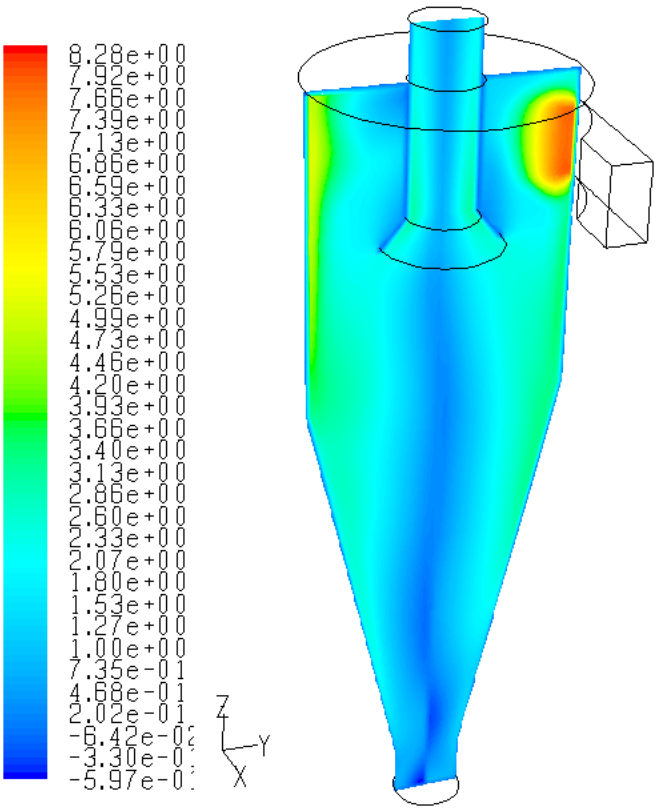


Figure C 4: Contours of tangential velocity 3rd case

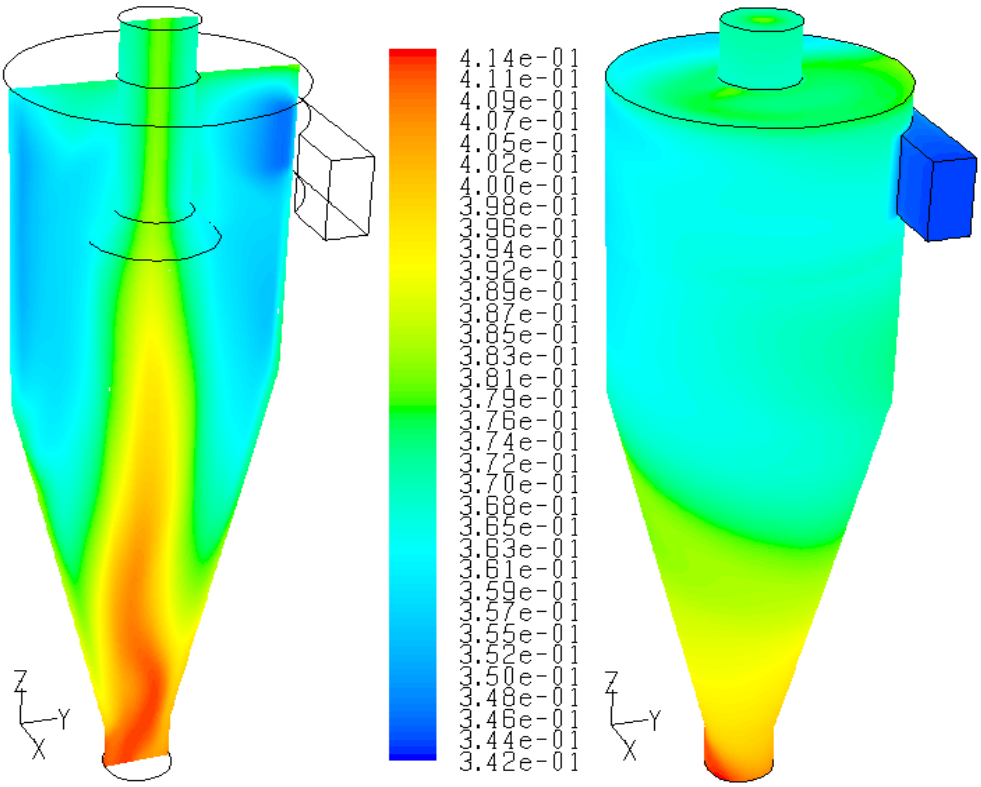


Figure C 5: Contours of density distribution 3rd case

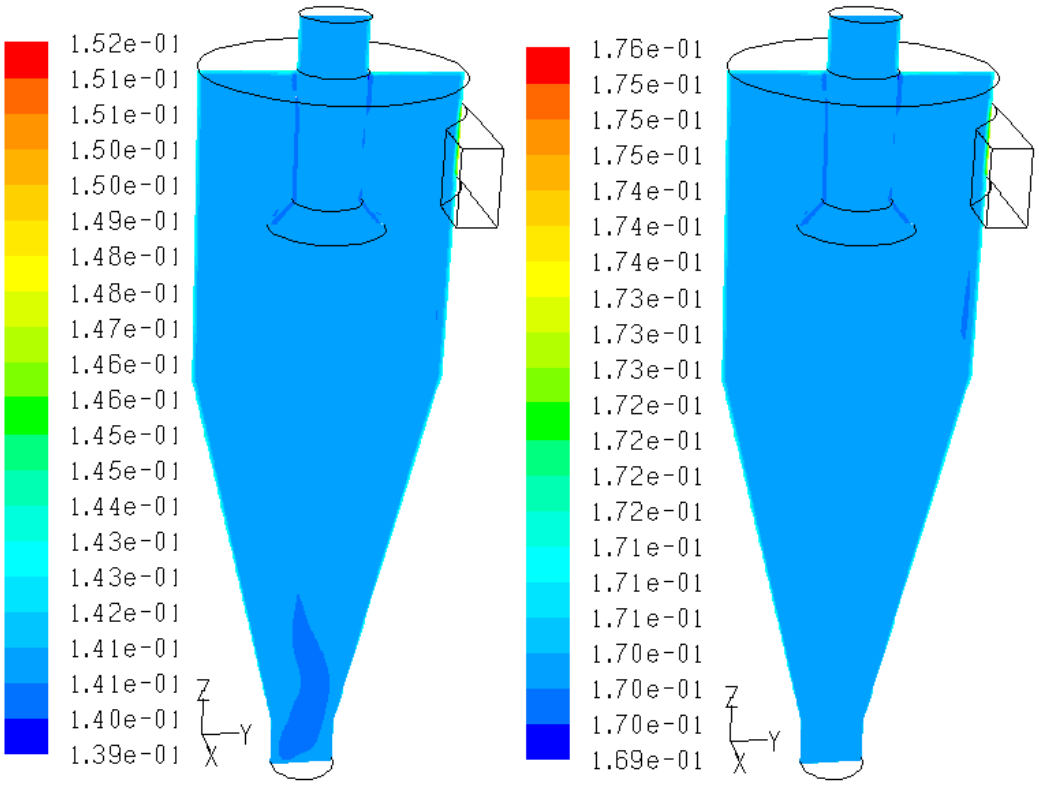


Figure C 6: Mass fractions of c3h6 and c2h4

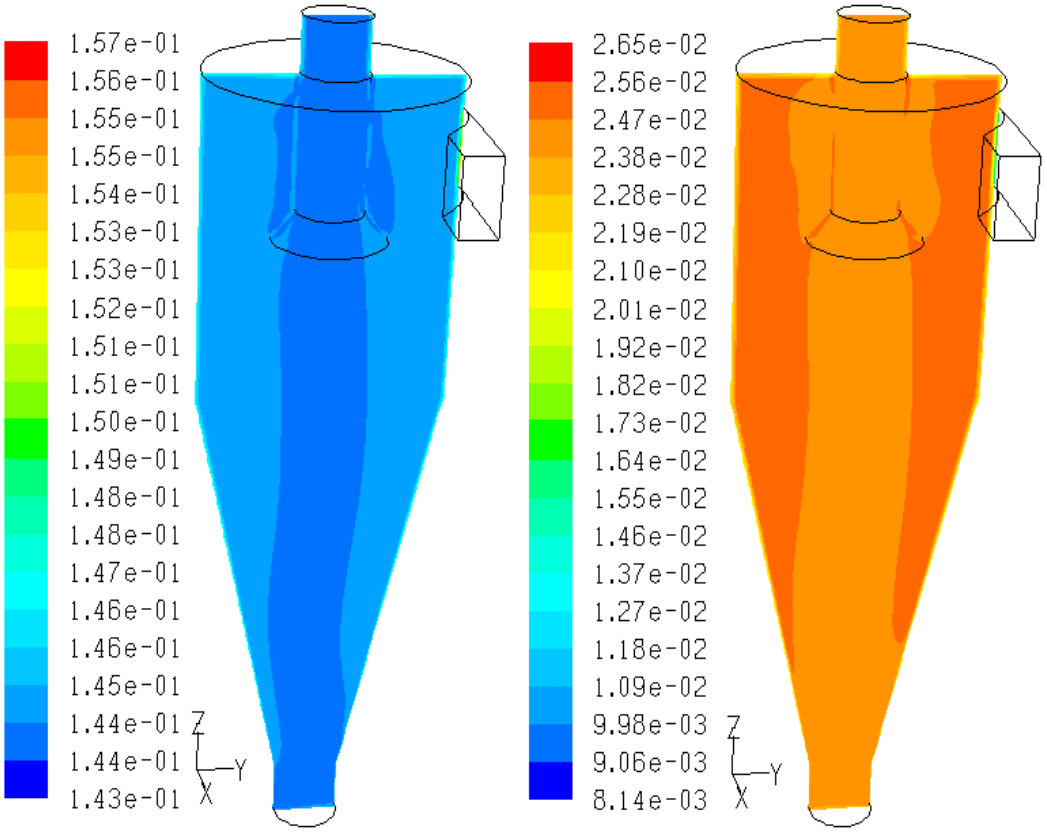


Figure C 7: Mass fractions of co2 and h2

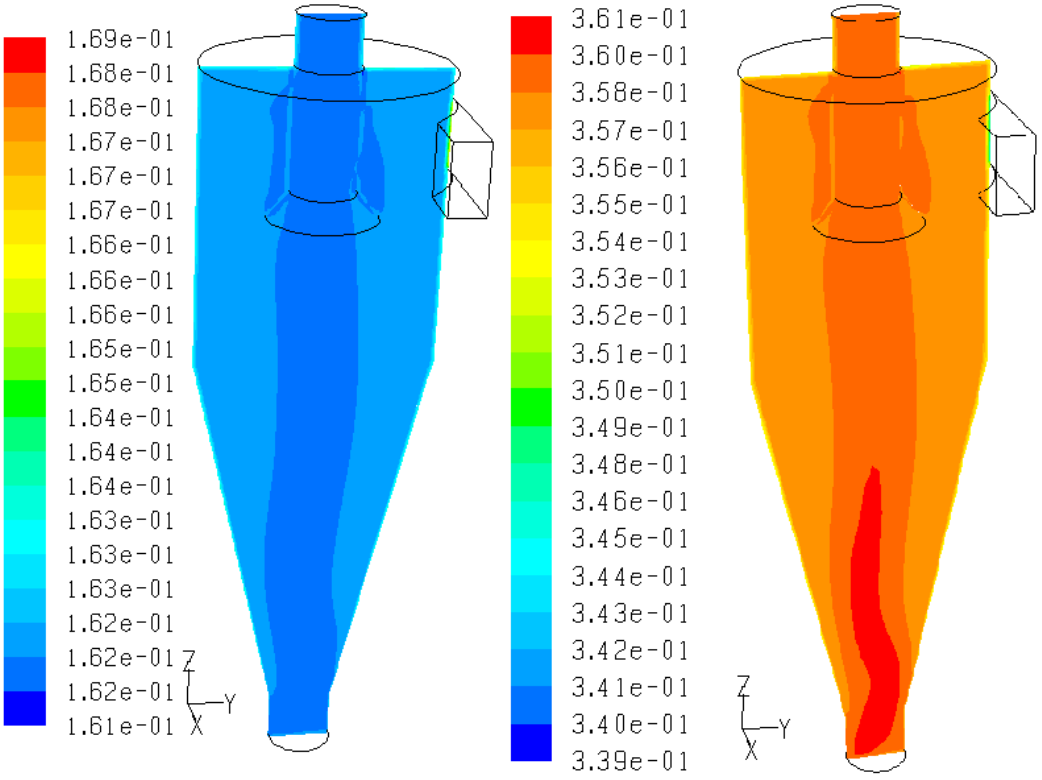
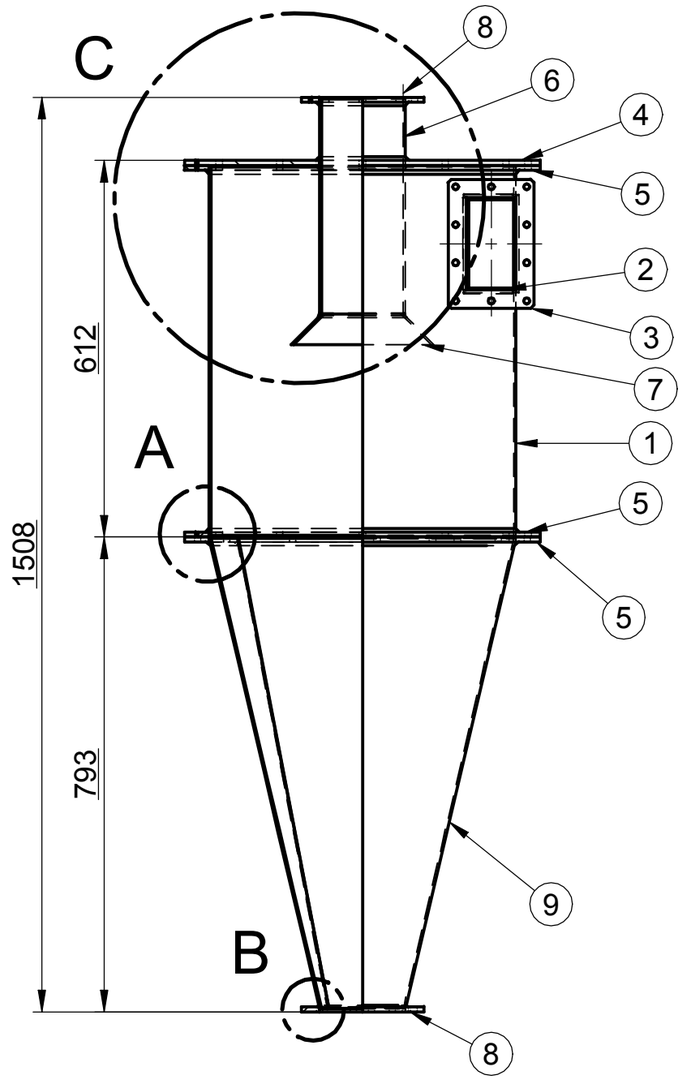
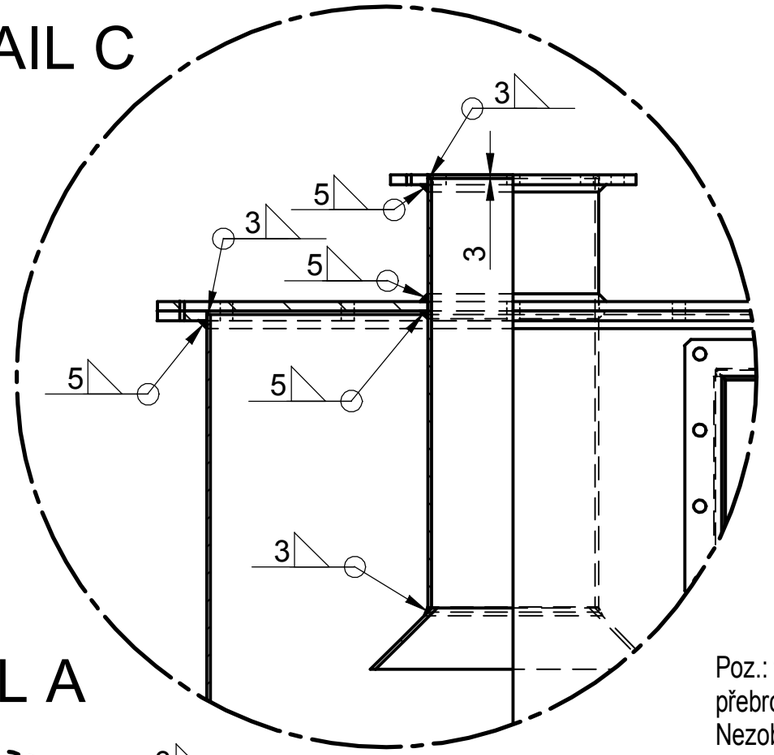
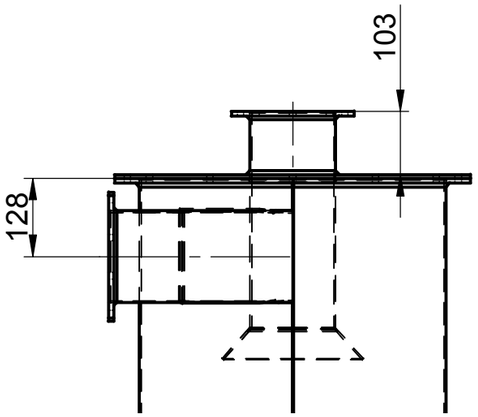
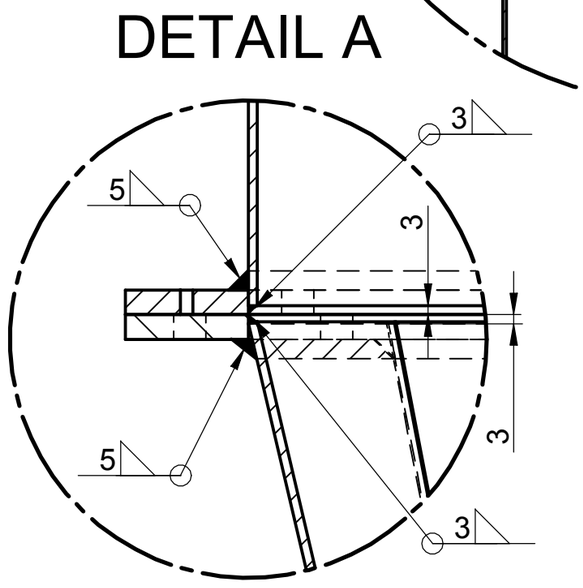


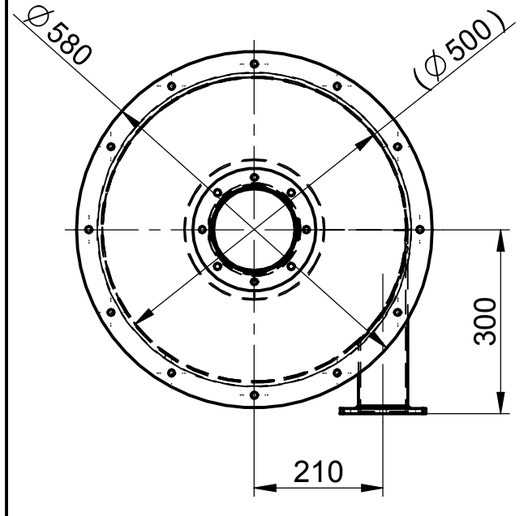
Figure C 8: Mass fractions of c2h6 and ch4

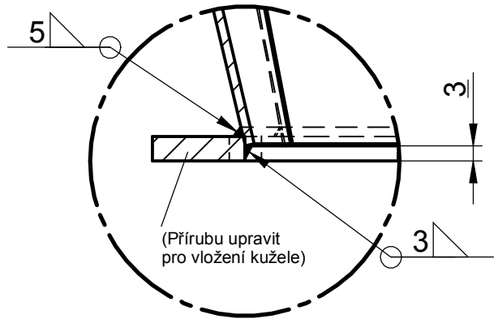












Poz.: vnitřní plochy cyklónu a čela přírub po svařování přebrousit/přelešťit.
Nezobrazeny šrouby a matice (bude upřesněno dodatečně poznamkou).

Item Number	Document Number	Title	Material	Quantity	Hmotnost
1*	4D-0829/Arr	Válec cyklónu	Stainless steel	1	21,0 kg
2*	4D-0830/Arr	Vstup cyklónu	Stainless steel	1	2,0 kg
3*	4D-0803/Arr	P□íruba vstupu	Stainless steel	1	1,0 kg
4*	4D-0828/Arr	Víko cyklónu	Stainless steel	1	11,5 kg
5*	4D-0827/Arr	P□íruba cyklónu	Stainless steel	3	12,4 kg
6*	Tr 139,7 x 3 - 350 mm (1.4828)	Tr 139,7 x 3 - 350 mm (1.4828)	Stainless steel	1	3,6 kg
7*	4D-0832/Arr	Nástavec cyklónu	Stainless steel	1	0,9 kg
8*	4D-0801/Arr	P□íruba D139	Stainless steel	2	1,9 kg
9*	4D-0831/Arr	Ku□el cyklónu	Stainless steel	1	18,7 kg

Počet kusů: 1	Název - Rozměr	Polotovar		Mat. konečný	Mat. výchozí	Čistá váha	Č. výkresu sestavy / Pozice
			c)	PŘESNOST ISO 2768-fH			
			b)	TOLEROVÁNÍ ISO 8015		Celk.hmotnost v kg	73,8 kg
			a)	PROMÍTÁNÍ		Skupina	
Změna		Datum	Index	Podpisy			
Měřítko 1:10	Pozn. Projekt: Pyrolýza VŠB	Navrhl		Robert Dvořák, DiS.			
		Kreslil		Robert Dvořák, DiS.			
		Přezkoušel					
Č. kusovníku		Technolog					
Č. sestavy		Normalizace					
Starý výkres		Schválil					
Nový výkres		Datum		5.11.2008			

Název

Sestava - Cyklón

Arrow line, a.s. Ostrava

www.arrowline.cz

Číslo výkresu

3D-0578/Arr